Hes·so VALAIS WALLIS
School of Engineering

Hes·so
Haute Ecole Spécialisée de Suisse occidentale
Fachhochschule Westschweiz
University of Applied Sciences and Arts Western Switzerland

Degree Programme
Systems Engineering

Major Infotronics

Bachelor's Thesis Diploma 2017

Chalokh Sara

XF operating system

Professor
Medard Rieder

Expert
Patrick Amborb

Submission date of the report
25.08.2017

HES-SO Valais-Wallis • rte du Rawyl 47 • C.P. • 1950 Sion 2
+41 27 606 85 23 • hei@hevs.ch • www.hevs.ch

Valais excellence

Project summary

The Embedded Communication System group (ECS Group) dispose on its own developed Execution Framework (XF). This actual version is not adapted for a real-time operating system (OS) such as Free RTOS, Zephir-OS or similar.

This Bachelor thesis has for purpose to develop, test and document an XF than can be put on the top of an OS or RTOS. The interface of the XF should not depend on the used OS it must therefore implement an operating system abstraction layer (OSAL)

This document presents the specifications of the project, a brief description of the actual execution framework, an analysis of the Free RTOS primitives and a first solution to mix them. Then will come the development of the project and the tests realized.

Table des matières

II. List of acronyms

Acronym	Real word
API	Application Programming Interface
ECSG	Embedded Communication Systems Group
gtest	Google test
OS	Operating System
OSAL	Operating System Abstraction Layer
RTOS	Real Time Operating System
UART	Universal Asynchronous Receiver Transmitter
XF	eXecution Freamwork
XFOS	eXecution Framework Operating System

III. Introduction

This project takes place in the embedded system programming, an increasingly domain in the world of today. The embedded system programming is purely informatics, but it needs strong skills in electronic to understand exactly the work of the system. Low resources offered by embedded system impose strong constraints on the processing time, memory usage, power consumption and security. In parallel embedded systems must carry out more and more complex tasks.

To carry out their work, many embedded systems realize a series of actions depending on a sequence of events with which they are presented. This series of actions is named a state machine. Most of embedded systems uses this concept because it separates the work into a set of simple tasks. Nowadays, the operating systems used in the embedded systems are not adapted to execute state machines. The programming concept used to execute state machines is the execution framework.

The goal of this project is to developpe or adapt an operating system to make it can execute state machines.

The Embedded Communication System Group (ECS Group) working in the HES-SO Valais/Wallis has developed its own execution framework. But this one works without any operating system. It means that it could not work with an OS or RTOS and, thereby, cannot enjoy the benefits offered by a real OS. Such as, multi-threading, memory management or mutual exclusion.

This project aims to develop an execution framework to put on the top of the real-time operating system Free RTOS. The programming language used is the C++, a language very used in the embedded system world and that is object oriented. The project must be developed in order to be adapted for other operating systems. Therefore, it must propose an operating system abstraction layer.

In the beginning, the new XFOS should have been implemented on the base of an ARMEBS4 (cortex M4F), but during the project, it has been changed to the STM32F412 Discovery kit from ST Microelectronics.

All new elements and programmer interfaces should be presented in the form of a set of UML diagrams.

Every solution must be tested and documented.

Finally, a complete documentation must be established, this include:

- A WIKI documentation for the new XFOS
- A complete unity test for every solution using Google test
- A final report

IV. The actual execution framework

1. What is an execution framework?

An XF provides a collection of services that allow asynchronous communication and execution of objects and of reactive entities containing state machines [1]. When XF is used with an OS, it is an abstraction layer between the OS and the user's applications. When it is used without OS, it is an interface and provides some important functions of an OS such as synchronization, pseudo parallel execution and a high abstraction degree.

The XF offers a simple interface that do not depend of a specific OS, it allows methods to implement state machines, that is very adapted to embedded requirements. The code size of an XF is small and it can be developed in any programming language.

The Figure 1 presents the class diagram of all the XF.

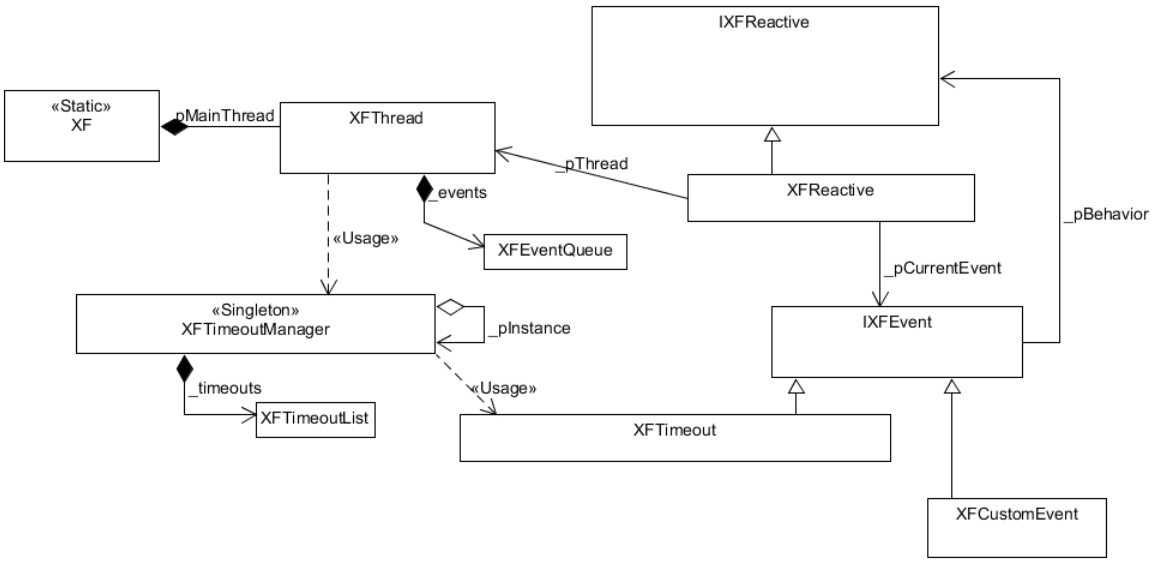


Figure 1 : Class diagram of the XF

2. How work the ECSG XF

The ECSG XF works with the combination of State machines (XFReactive) these will execute some code and move forward the program, and Events that will change the actual state of the state machine.

State machines contain the core of the application developed by the user.

Events are sent to the thread (XFThread) by state machines when they have finished executing the code of their actual state. One time sent by state machines, events are stored in a queue and wait to be processed.
When an event is processed, it is sent to the state machine and this one (in function of the information of the event and the actual state) will change its actual state and execute the code of the new state.

Some events could need a delay before being processed. To do this, the XF uses a timeout manager and timeouts. In the ECSG XF, when state machines would send an event with a delay they must call the timeout manager and schedule a timeout. When the time specified ends, the timeout manager will notify the state machine that a timeout occurs.

The processing of an event

The ECSG XF is made of one thread where are living all state machines, and an event queue that contains events of state machines. To execute state machines, the XF reads the first event of its event queue and dispatch it to the good state machine. When a state machine receives an event, it goes in a new state and executes its code, finally the state machine sends a new event to the event queue to start the next state.
At the begin all state machines are in an initial pseudo state and they send an initial event to start.
The sequence diagram of the Figure 2 presents this process.

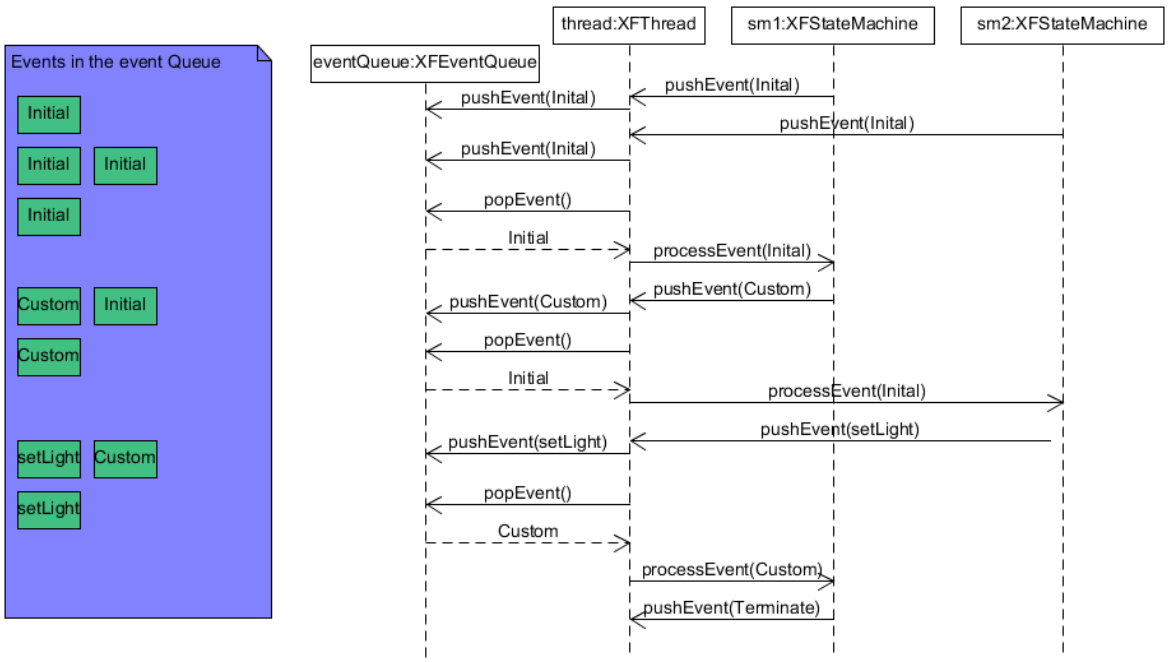


Figure 2 : The ECSG XF processing of an event

The timeout manager

The ECSG XF offers the possibility to use timeouts. Timeouts are special events that have a delay before being sent to the state machine. Timeouts are managed by a timeout manager. This one contains a timeout queue where are stored all active timers. When a timer ends, the timeout manager notifies the state machine that push the event to the event queue.

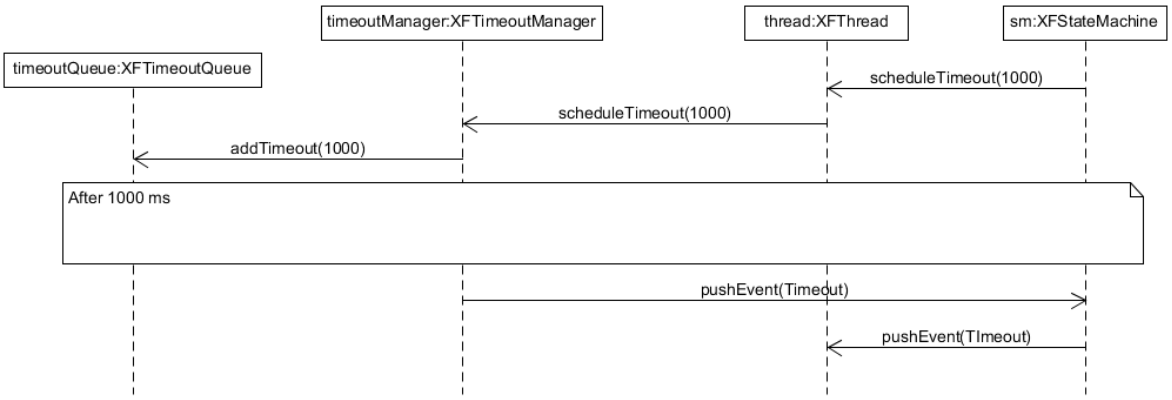


Figure 3 : the ECSG XF processing of a timeout

The management of timeouts

The creation of an independent timer in an embedded system is not possible because the number of hardware timers is limited. Another solution is to use only one hardware timer with a short period (tick) and update all software timers of the timeout list. This solution is right but it poses a problem because the time to update all timers depend on the number of timers in the queue, this is not acceptable for a real-time system.

The method proposed in the ECSG XF is to use timeouts with 2 values:

- timeoutTicks: the time to wait in tick (ticks are the hardware timer's period)
- remainingTicks: the number of tick to wait before the timer timeout

The difference with the second solution takes place when a timer is added in the queue, instead of adding the timer at the end of the queue, the timer manager will browse the queue and search the first timer that the number of remainingTicks is lower than the timeoutTicks of the timer to add. Once found the timeout manager adds the new timer just before it and update the remainingTicks of the new timer.

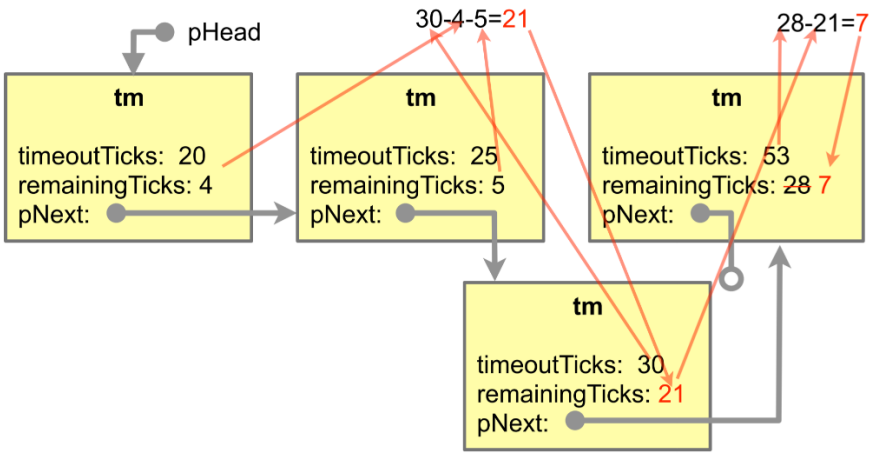


Figure 4 : How and where add a new timer in the ECSG XF
Source: XF optimized timer management, ©HES-SO Valais/Wallis [2]

The timeout list is updated every tick, but in the 3rd solution, only the first timer of the queue is decremented. If the remainingTick of the first timer is 0, also the timeout manager notifies the state machine.

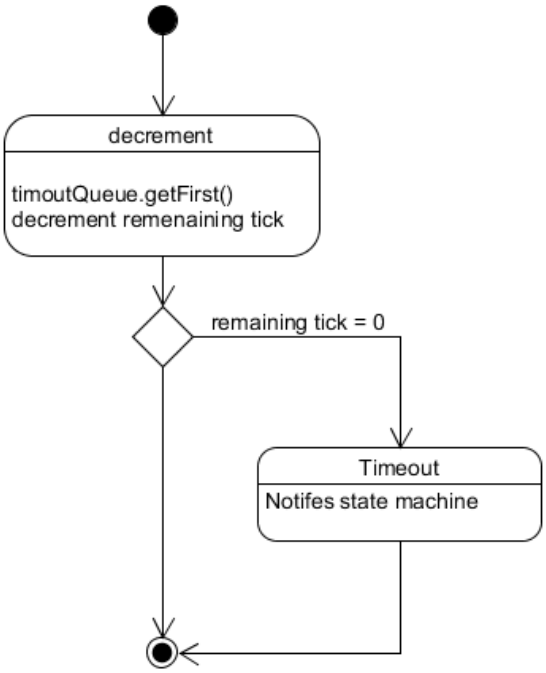


Figure 5 : flow chart of the method tick()

V. Free RTOS primitives

To develop the execution XFOS, the Free RTOS primitives needed are:

- taskHandle_t: the thread of Free RTOS
- queueHandle_t: queues that can be used for an inter-task communication
- timerHandle_t: a software timer from Free RTOS
- semaphoreHandle_t: a semaphore (or mutex) from free RTOS

taskHandle_t

An application that uses an OS is structured as a set of tasks that are independent. All these tasks have their own context, their own stack and their own main function. Only one of them can be executed in the processor at any point of time. The scheduler is responsible for deciding which task is executed at a given time.

The taskHandle_t is an independent task that is scheduled by the Free RTOS scheduler. A taskHandle_t has its own stack and when a task is swapped, the processor's context (register values, stack contents, etc) is saved on the top of this stack, so it can be exactly restored when the task is later swapped back.

A taskHandle_t could be stopped after a certain amount of time of the processor usage or if it tries to access a used resource.

queueHandle_t

Queues are, in Free RTOS, the primary form of inter-task communication. It can be used to send messages between tasks or between tasks and interrupts. In Free RTOS, queue messages are sent by copies, it means that the data is itself copied into the queue rather than the queue always storing just a reference to the data.

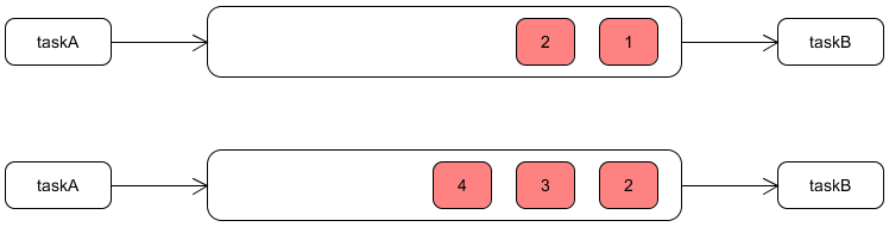


Figure 6 : Messages send between 2 tasks

Free RTOS queues offer also the possibility to suspend or wake up a task. For example, if a task tries to read a queue and this one is empty, the task will automatically wait until a message arrives in the queue.

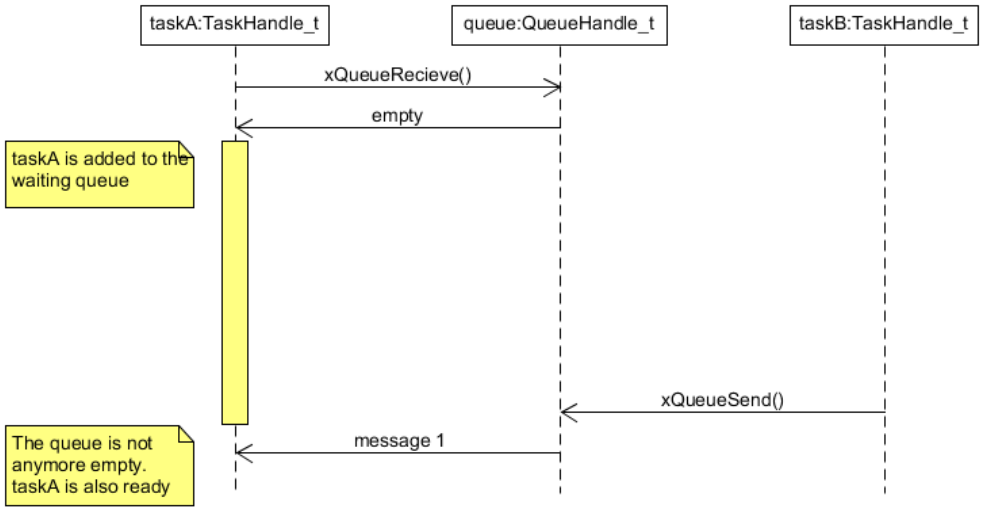


Figure 7 : Task waiting for a queue

In Free RTOS, it is possible to define a maximal amount of time that a task that need to use a queue must wait in the waiting state. If this time expired, the function will just return a value that indicates that the operation fails.

TimerHandler_t

TimerHandle_t is a software timer, it allows a function to be executed at a set time in the future. This function is called a callback function. In the Free RTOS implementation timers do not use any processing time unless a timer has expired, it does not execute callback function in an interrupt context and does not add any processing time to the tick interruption [3].

All timers use the timer service task. This task is private to the Free RTOS implementation and cannot be accessed directly. It manages all timers and tries to use minimal resources. The Free RTOS API provide a set of functions to manage timers. Many of these functions use a simple Free RTOS queue to send timers to the timer service task.

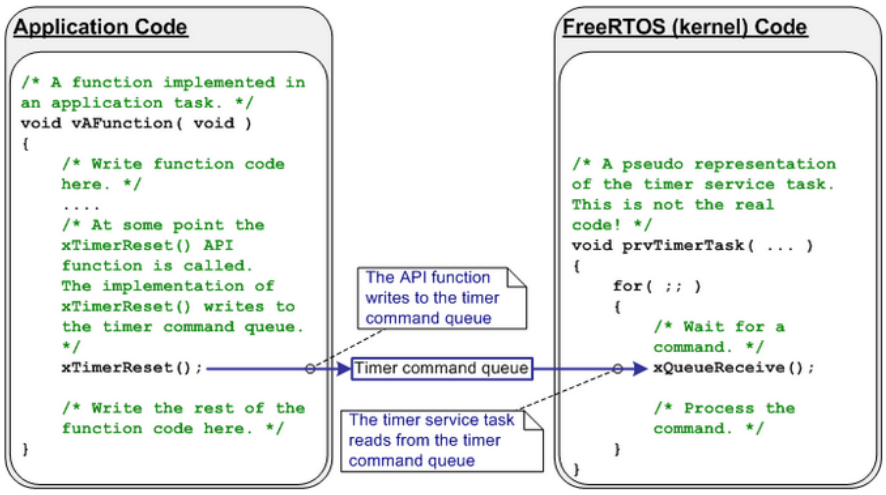


Figure 8 : The call of a Free RTOS timer function
Source : Software timer, Timer service/daemon task, www.freertos.org [4]

SemaphoreHandle_t

The SemaphoreHandle_t is the base used by Free RTOS to implement counting semaphore, mutex and binary semaphore. They are used to protect critical sections and implement a synchronization.

In Free RTOS, it is possible to define a maximal amount of time that a task that need to take a semaphore must wait in the waiting state. If this time expires, the function will just return a value that indicates that the operation fails.

Counting semaphore

A counting semaphore is created by calling xSemaphoreCreateCounting(). A counting semaphore is the classic semaphore used to allow a resource to a defined number of users.

Binary semaphore and mutex

Binary semaphore and mutex are semaphores initialized to 1. Binary semaphores and mutexes are very similar but they present some subtle differences. Mutexes include a priority inheritance mechanism, binary semaphores do not. It means that the priority of a task that 'takes' a mutex can potentially be raised if another task of higher priority attempts to obtain the same mutex. The task that owns the mutex 'inherits' the priority of the task attempting to 'take' the same mutex. This means the mutex must always be 'given' back - otherwise the higher priority task will never be able to obtain the mutex, and the lower priority task will never 'disinherit' the priority. This makes binary semaphores the better choice for implementing synchronization (between tasks or between tasks and an interrupt), and mutexes the better choice for implementing simple mutual exclusion [5]

VI. Solutions

The primary difficulty of this project is to use Free RTOS primitives in a C++ project, because Free RTOS is coded in C. To simplify, all Free RTOS primitives are encapsulated in C++ objects. These objects provide an interface to manage primitives. This approach greatly simplifies the development for some others OS because only classes that uses OS primitives must be changed. For the user, the interface does not change from an OS to another.

The Figure 9 present the solution for the implementation of the XFOS.

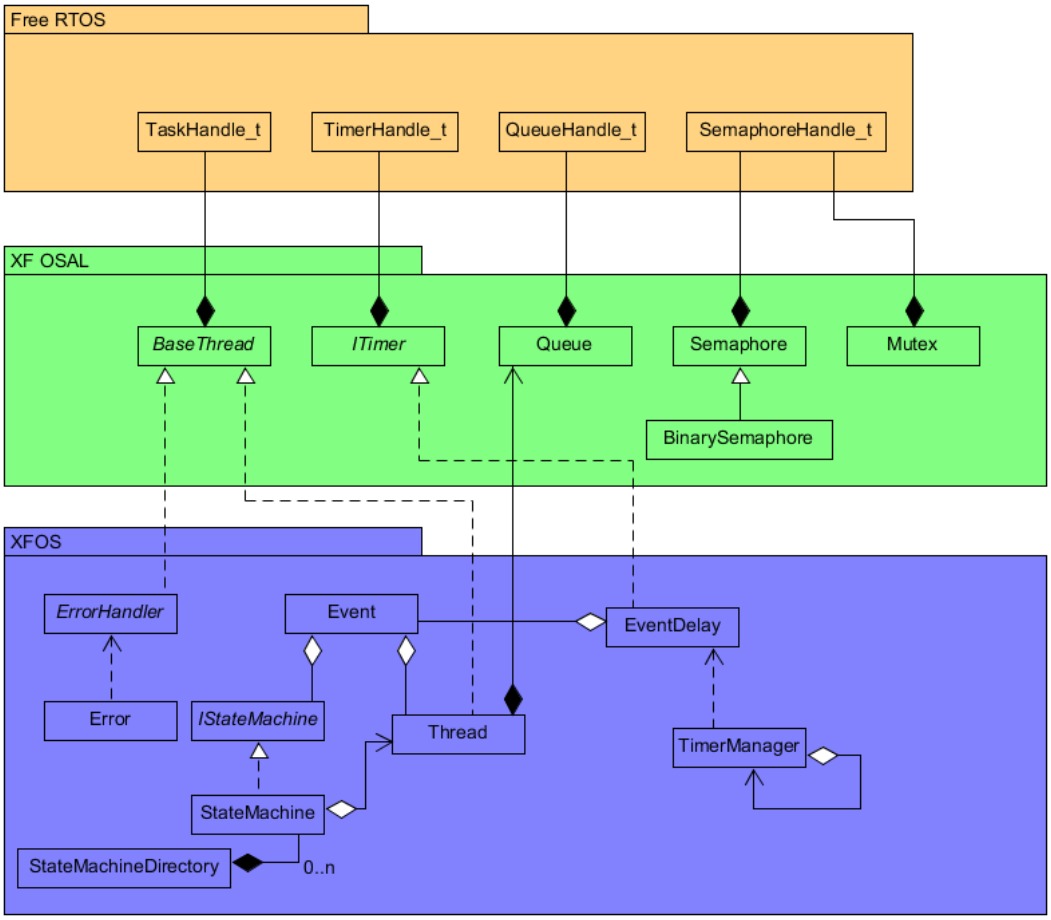


Figure 9 : XFOS implementation

The package XF OSAL is the part implemented to abstract the OS primitives. This part is independent from the XF work.

The package XFOS implements classes used to make the XF works. It is very different from the ECSG XF, but some classes just change name, their work is the same as the XF.

The Table 1 presents classes that have changed their name.

Class name in XFOS	Class name in ECSG XF
IStateMachine	IXFReactive
StateMachine	XFReactive
Event	IXFEvent
TimerManager	TimeoutManager
EventDelay	XFTimeout
Thread	XFThread

Table 1 : Name changement between XFOS and ECSG XF

Some classes do not exist in the ECSG XF that are: ErrorHandler, Error and StateMachineDirectory. These classes are presented in section 2 and 3 of this chapter.

1. Differences with the ECSG XF

The principal difference between ECSG XF and XFOS is the multitasking. In the XF all state machines (behaviors) leave in the same thread. With the XFOS, state machines can be in different threads (but several state machines can still live in the same thread). A thread has its own event queue shared by all state machines that live on it.

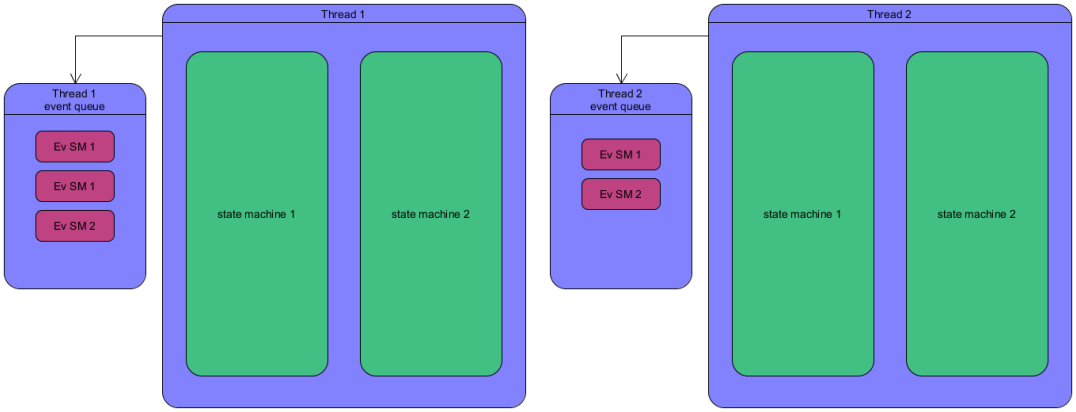


Figure 10 : Multitasking in XFOS

Timeout and Events

In the ECSG XF, Timeouts are different from simple events. State machines have to use a special function in order to use a timeout.

In the XFOS timeout has been removed and events could now have a delay time. It's the work off the thread, to determine if the event must be sent to the timer manager or directly push in the event queue, when a state machine asks to add an event. This method is simpler for the user because he just need to set delay time to 0 if he does not want a delay.

The operating is presented in Figure 11.

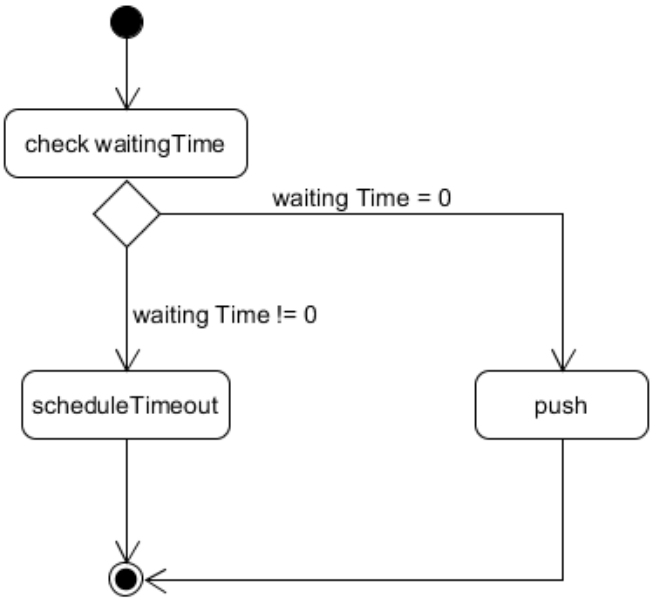


Figure 11 : XFOS thread, add an event to the event queue

When an event with a delay is asked by a state machine, the thread must call the private method schedule timeout. This method calls the timer manager to schedule a timeout. The thread sends to the timer manage a pointer to the event that needs a delay.

The Figure 12 shows the pushing of an event with delay

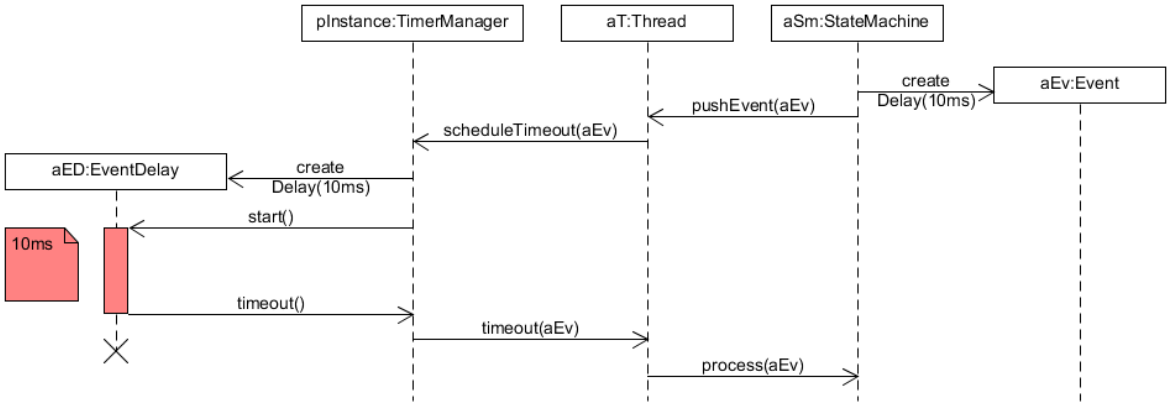


Figure 12 : XFOS, addition of an event with delay

When the delay time has expired, the timer manager notifies the destination thread. This one will set the delay of the event to 0 and push it to the event queue.

2. Error Handling

During the calling of some functions, it may be something unexpected. For example, if a thread is created but there is no memory space for it.

The Table 2 presents the list of functions those could not execute themselves correctly.

Function	Class
BaseThread()	BaseThread
setPriority()	BaseThread
restartFromISR()	BaseThread
forceRestart()	BaseThread
Queue()	Queue
initQueue()	Queue
push()	Queue
pushCopy()	Queue
pushFromISR()	Queue
pushCopyFromISR()	Queue
pop()	Queue
popFromISR()	Queue
Peek()	Queue
peekFromISR()	Queue
overWrite()	Queue
overWriteCopy()	Queue
overWriteFromISR()	Queue
overWriteCopyFromISR()	Queue
ITimer()	ITimer
setPeriod()	ITimer
setPeriodFromISR()	ITimer
start()	ITimer
startFromISR()	ITimer
stop()	ITimer
stopFromISR()	ITimer
reset()	ITimer
resetFromISR()	ITimer
Semaphore()	Semaphore
take()	Semaphore
takeFromISR()	Semaphore
give()	Semaphore
giveFromISR()	Semaphore
Mutex()	Mutex
enter()	Mutex
enterFromISR()	Mutex
exit()	Mutex
exitFromISR()	Mutex

Table 2 : XFOS functions those could generate an error

If one of those functions does not work as expected, it is important to inform the user. Therefore, they return a Boolean value that indicates if the function is correctly executed or not.

Return a Boolean value is not a bad idea but some functions on the Table 2 could not do it because they are constructors or they already return a value.

Functions that already return a value

These functions are not numerous they are only pop(), peek() and their derivatives. Those functions will simply return NULL if they cannot execute themselves correctly.

It is the work of the user to check if a function execute itself as expected.

The problem of constructors

Constructors do not return anything, so it is not possible to inform the user that something goes wrong. To solve this problem, all classes of with a constructor can work badly have a function isCreated() that will return a Boolean value to inform if the object has been created successfully.

Errors and ErrorHandler

The solutions presented before can indicate that something does not work as expected but they cannot tell precisely the source of the problem, so it is difficult to the user to solve the problem.

The best way to solve this problem would have been to use exceptions. But exceptions are not optimized for embedded systems.

So, the XFOS, in addition to implementing solutions presented before, also propose its own exceptions.

Errors are sent to the ErrorHandler by classes when something goes wrong. They contain some information about the problem that occurs to describe it more precisely.

The ErrorHandler is a thread with a higher priority than user thread. It can receive errors and execute some actions in consequence. Actions executed by the ErrorHandler are defined by the user. So, if he wants to use the ErrorHandler, he must create a subclass that inherits from it.

The user can define if he wants to use Errors and ErrorHandle in the XFOS_config.h. He just must comment or uncomment the line #define useErrorHandler.

3. Inter-task communication

The ECSG XF do not permit the inter-state machine communication. A state machine could only send an event to itself (except if it specifically knows the other state machine).

The XFOS propose a dynamic solution to send events between state machines. Whether they are in a same thread or in 2 different threads. This solution is the StateMachineDirectory. This class contains a list of pointers on all state machines. When a state machine is created, it is automatically added in the list and when it is deleted it is automatically removed from the list.

Every state machine could access to this directory and thus communicate with any other state machine.

The user has the possibility to disable the StateMachineDirectory. To do this, just comment the line #define useStateMachineDirectory in the file XFOS_config.h.

4. The XFOS_config.h

The XFOS uses some variable type specific to itself and some defined values. All these values are defined in the XFOS_config.h file.

Specific variables type

The specific variable types are mainly used to minimize the use of the memory. Those types are not different from the other basic types, they just replace an existing type by using a define.

The Table 3 presents all special types used in the XFOS and a definition of them.

Special XFOS type	Real type	Definition
timeSize	TickType_t	The integer value used to define a time
baseInt	int32_t	The basic integer value
baseUInt	uint32_t	The basic unsigned integer value
QUEUE_LENGHT_SIZE	uint8_t	The value defined to fit the maximal queue length
ID_SIZE	uint16_t	The value defined to fit the maximal ID length
PRIORITY_SIZE	uint8_t	The value defined to fit the maximal priority level
STACKSIZE_SIZE	uint16_t	The value defined to fit the maximal stack size

Table 3 : XFOS special types

The uppercase types are linked to the other defined values. For example, QUEUE_LENGHT_SIZE is linked to the defined value MAX_QUEUE_LENGHT. If MAX_QUEUE_LENGHT is set as 100 also an uint8_t suffice to fit it. If it is set as 500 an uint16_t is needed.

There is no maximal value defined for the ID so it is the maximal value of ID_SIZE that defines it. For example, if ID_SIZE is set as uint8_t, the maximal ID is 255.

Defined values

Defined values are used to make the XFOS independent from a specific OS. They can be defined by the user in the file XFOS_config.h.

The Table 4 shows all defined values used, their real value in the project and a definition of them.

Define	Value of the define	Definition
MAX_QUEUE_LENGTH	100	The maximal number of objects that a queue can contain simultaneously
THREAD_STACK_SIZE	128	The minimal size of the thread's stack (in words !!!)
LOW_PRIORITY	0	The minimal priority
MAX_USER_PRIORITY	5	The maximal priority that a user application can have
MAX_SYSTEM_PRIORITY	10	The maximal priority that a system application can have
INFINIT_TIME	portMAX_DELAY	Used to define a time that is infinite
TIMER_QUEUE_LENGTH	10	The maximal number of timer that the timer queue can contain simultaneously

Table 4 : Defined values of the XFOS

VII. Architecture

This section describes all classes of the project, it will explain their implementation and every choice that has been made.

The block diagram of the Figure 13 shows all basic classes and their connections.

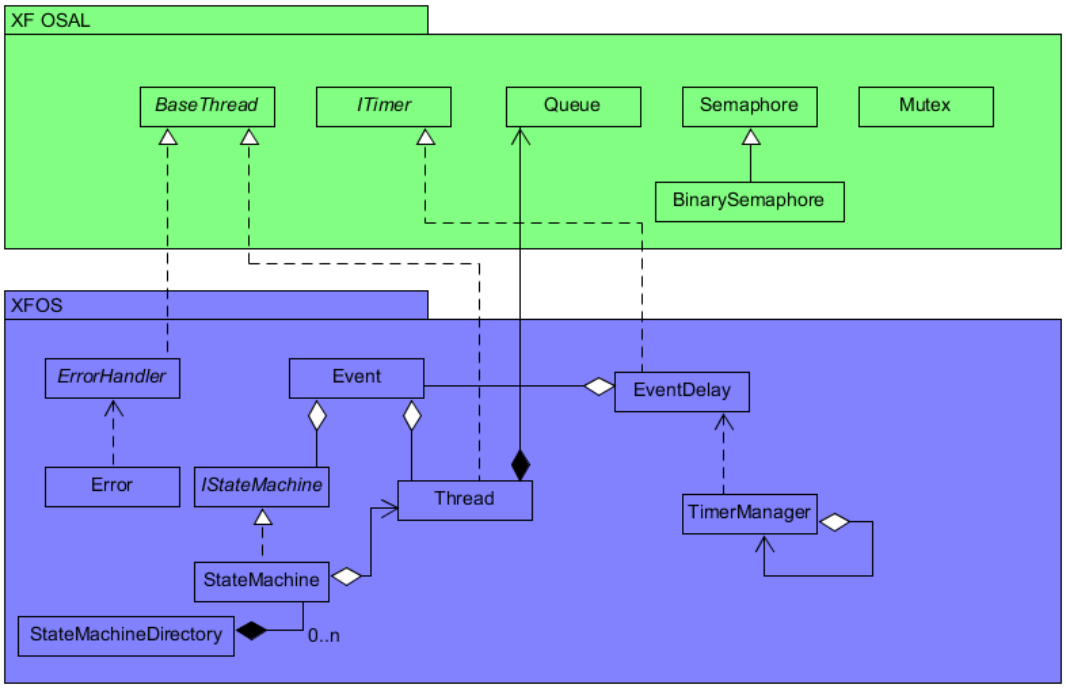


Figure 13 : Class Diagramm of the XFOS

Classes in the XFOSAL package directly depends of the Free RTOS primitives and must be reimplemented if another OS is used.

Finally, classes in XF package are OS independents and does not need to be reimplemented.

All classes of XFOSAL and XF will be described more precisely in the remainder of this document.

1. OSAL Package

Classes of the OSAL package are interfaces to manage Free RTOS objects. These classes need to be reimplemented if another OS than free RTOS is used or if the XF must be used as an IDF.

Queue

Queue is a central element of the XFOS. It is used by Threads to store events that are waiting for a processing. It is also used by ErrorHandler to handle errors that can occur during the execution.

At the beginning Queues was designed only for the use of the XFOS and they could contain only Events, but this approach was too much restrictive for the user.
For example, if the user does not want to use Event provided by XFOS but its own type of Events, he cannot.
This is why, it has been decided that queue could contain everything.

The implementation of this class is very simple, it just contains a private attribute QueueHandle_t (the Free RTOS queue) and all its method just call Free RTOS function for it.

The class diagram of the Figure 14 shows the class Queue and all its methods.

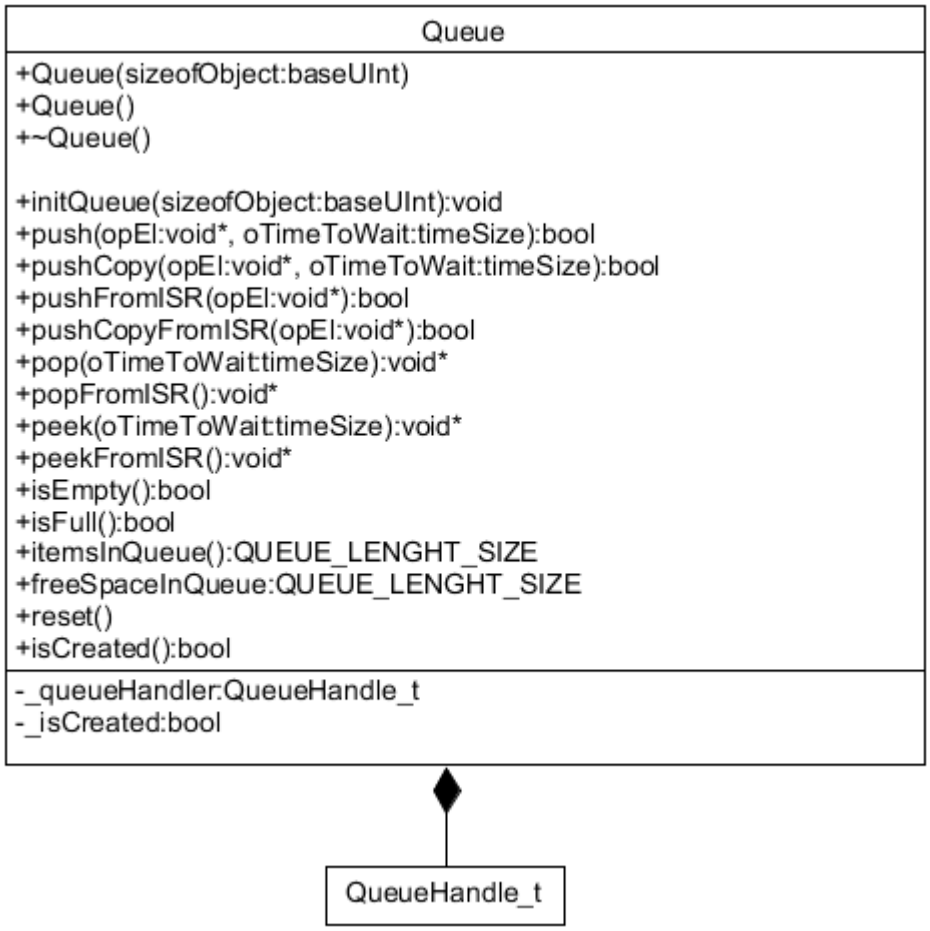


Figure 14 : Class diagram of Queue

Pointer queue and copy queue

Queue can contain copies of elements or pointers to elements.

The Figure 15 shows the difference between pointer queue and copy queue. The element to push is in the red square and the blue square is where the element is popped.

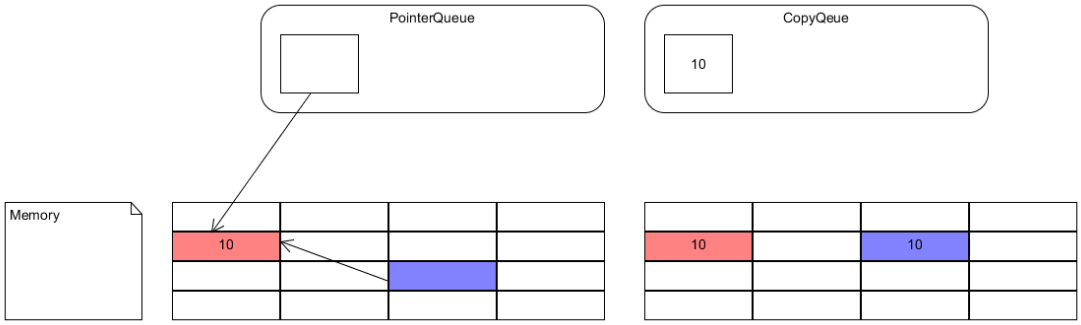


Figure 15 : Pointer Queue and Copy Queue

With the pointer queue, only a pointer to the element is pushed in the queue. Depend on the size of the element this method needs less memory than using copy, but if the elements is deleted the memory pointed by the pointer in the queue is wrong. It can result in a bad memory access and a hard fault in the worst case.

With the copy queue the element is pushed by copy this means that if the element is deleted it does not affect the copy in the queue. But if the element is changed after he has been pushed the copy is not affected.

Using a pointer queue or a copy queue implies that the push action is different, to push an element in a pointer queue the user must use the method push else he must call pushCopy.

What happen if user tries to use push on a copy queue?

It's a pointer to the element that is pushed in the queue and when he tries to pop it the value is totally wrong because it's a pointer.

The Figure 16 describes what happen if the element to push is an int. Red square (its address is 0x3204) is the element to push and blue square is where the element is received.

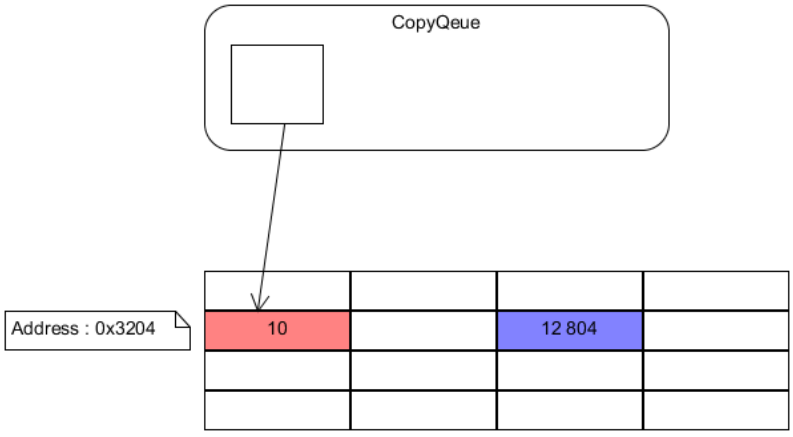


Figure 16 : Method push in a copy queue

Here the value popped is 12 804 it corresponds to 0x3204 that is the address of the red square.

What happen if user tries to use pushCopy on a pointer queue?

In this case the element popped is considered as a pointer but the queue contains an element so the popped value will point in a random place in the memory as shown in the Figure 17

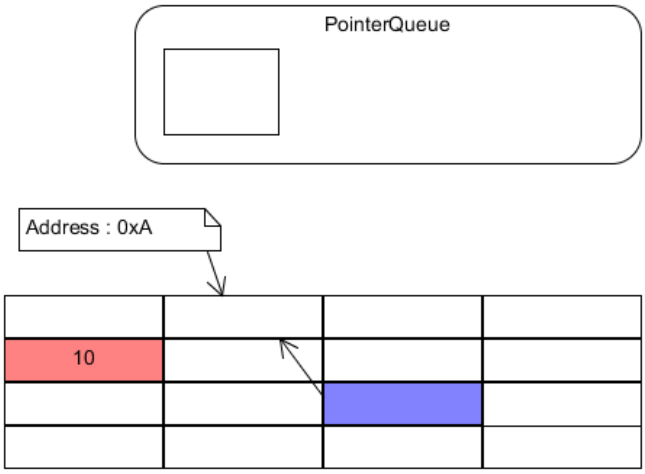


Figure 17 : Method pushCopy in a pointer queue

Semaphore

Semaphores are essential elements for a multi-task application. Also, if they are not used for the implementation of the XFOS, the class Semaphore has been implemented for the user application. As for the Queue, Semaphore just use Free RTOS function and adapt them for a C++ object.

Figure 18 is the class Diagram of the semaphore.

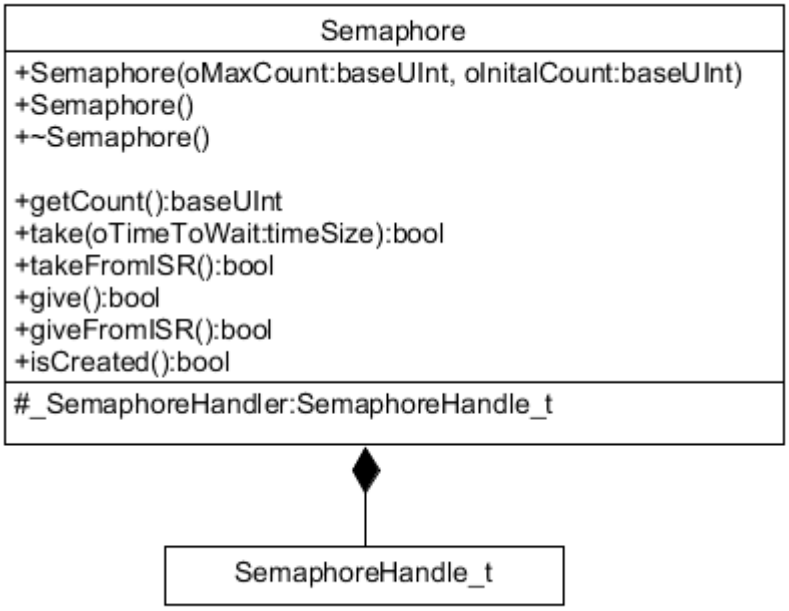


Figure 18 : Class diagram of Semaphore

Binary Semaphore

Binary Semaphore is semaphore that can be taken only once. This is very like Mutex but Mutex include a priority inheritance mechanic. Binary semaphore not.

Binary semaphores are principally used to implement synchronization (between tasks or between tasks and an interrupt).

Binary semaphores are not used in XFOS implementation but they have been developed for user applications.

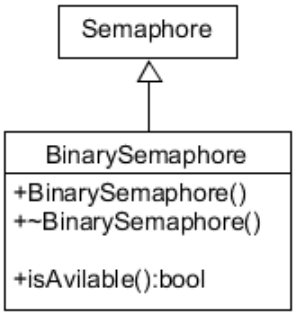


Figure 19 : Class diagram of Binary Semaphore

Mutex

Mutexes are like BinarySemaphores but they include an inheritance mechanism. This means that if a high priority task blocks while attempting to obtain a mutex (entered) that is currently held by a lower priority task, the priority of the task holding the token is temporarily raised to that of the blocking task. This mechanism is designed to ensure the higher priority task is kept in the blocked state for the shortest time possible, and in so doing minimize the 'priority inversion' that has already occurred [5].

This mechanism make that Mutexes are the best choice for implement mutual exclusion and protect critical sections.
Methods used to take and give the mutex have been named respectively enter and exit (because we enter in a critical section and we exit from it)

Mutexes are not used in the XFOS implementation but they have been implemented for the user application.

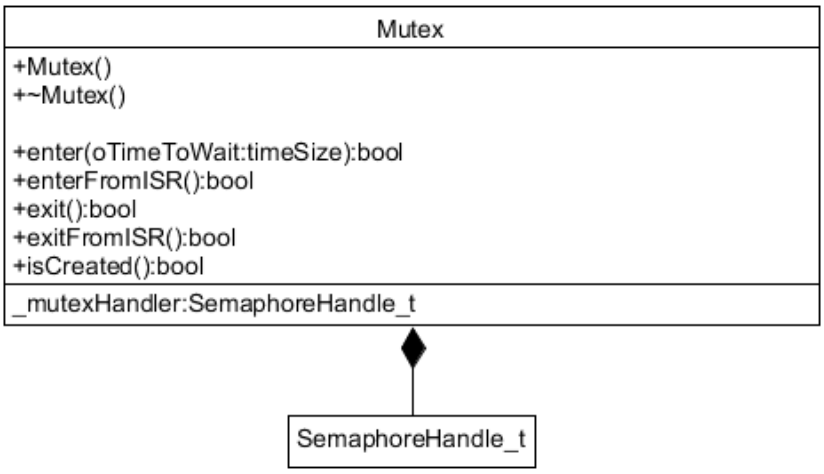


Figure 20 : Class diagram of mutex

BaseThread

This class is a C++ version of Free RTOS tasks, it is an interface that implements all Free RTOS functions to manage a Free RTOS task.

BaseThread implements also the main function of the thread, but in this class, it is just a pure virtual function that needs to be implemented on a sub class.

The Figure 21 shows all methods and attributes of the class BaseThread.

In a normal usage of the XFOS, this class should not be used directly by the user, because it is just an interface with Free RTOS.

If the user wants to create its own XFOS thread use the class Thread. This one provides specific methods for manage events and state machines. Else if the user does not want the XFOS but just want to use Free RTOS with C++ objects, this class is very useful.

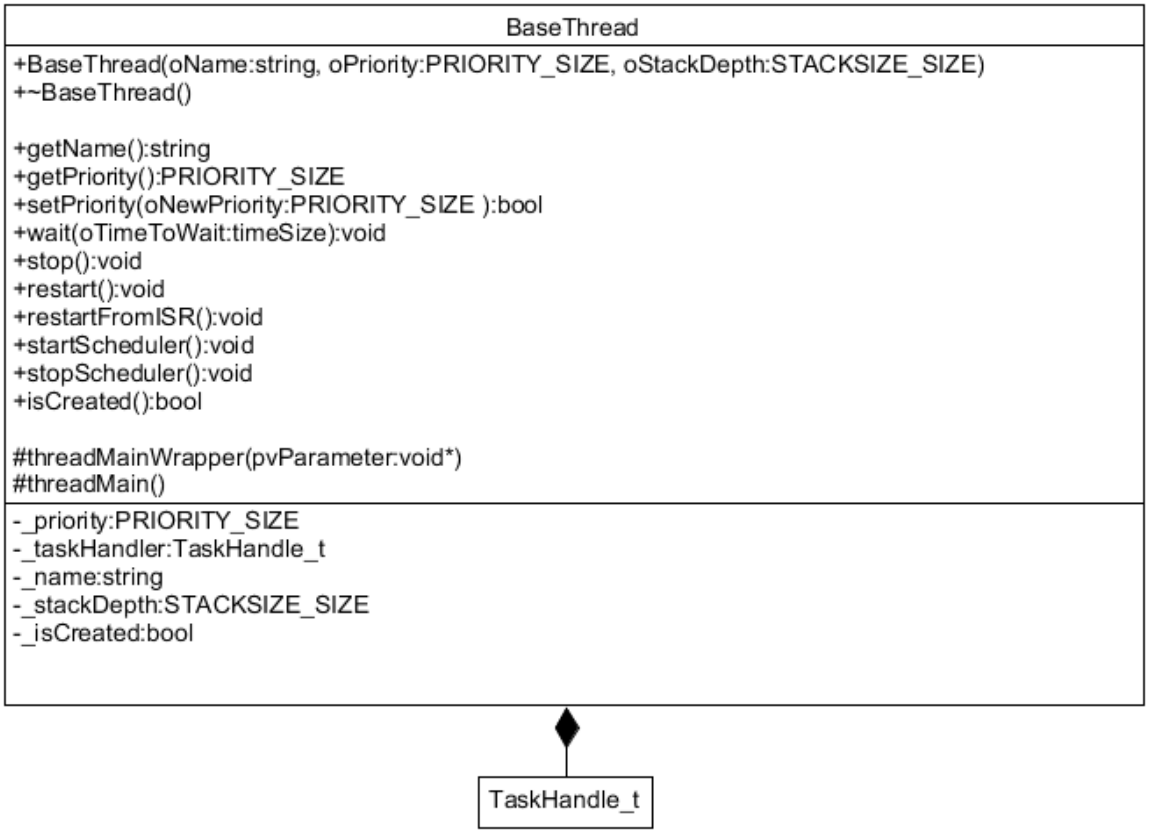


Figure 21 : Class diagram of Base Thread

ThreadMainWrapper

The Free RTOS tasks always need a function that will be the main function of it. But this function is just a simple C function that can be called from everywhere.

In C++, it is possible to define methods for a class. So, it is better if the main function of a thread is a method of this thread.

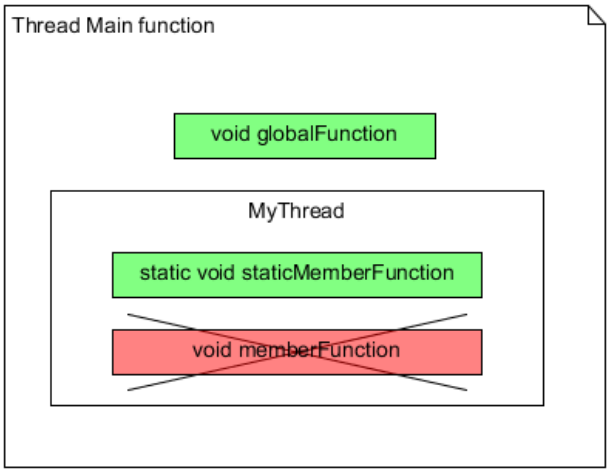


Figure 22 : Possible thread main functions

The problem is that the thread main function need to be with a "C" linkage [6].

Therefore, it could not be a simple member function. It can only be, in the better way, a static member function.

Using a static member function is not a good way because it means that every thread has the same main function (same sub classes) and it is not the goal.

To solve this problem, it exists 2 solutions:

- Using the callback method pattern
- Using a void pointer that points to the object thread

Callback method pattern

The callback method pattern provides a lightweight callback mechanism between different layers. It offers a maximum decoupling between layers and is very safe for the application [7].

This pattern is very similar to the observer pattern.

In the context of the thread this pattern could be represented in the Figure 23.

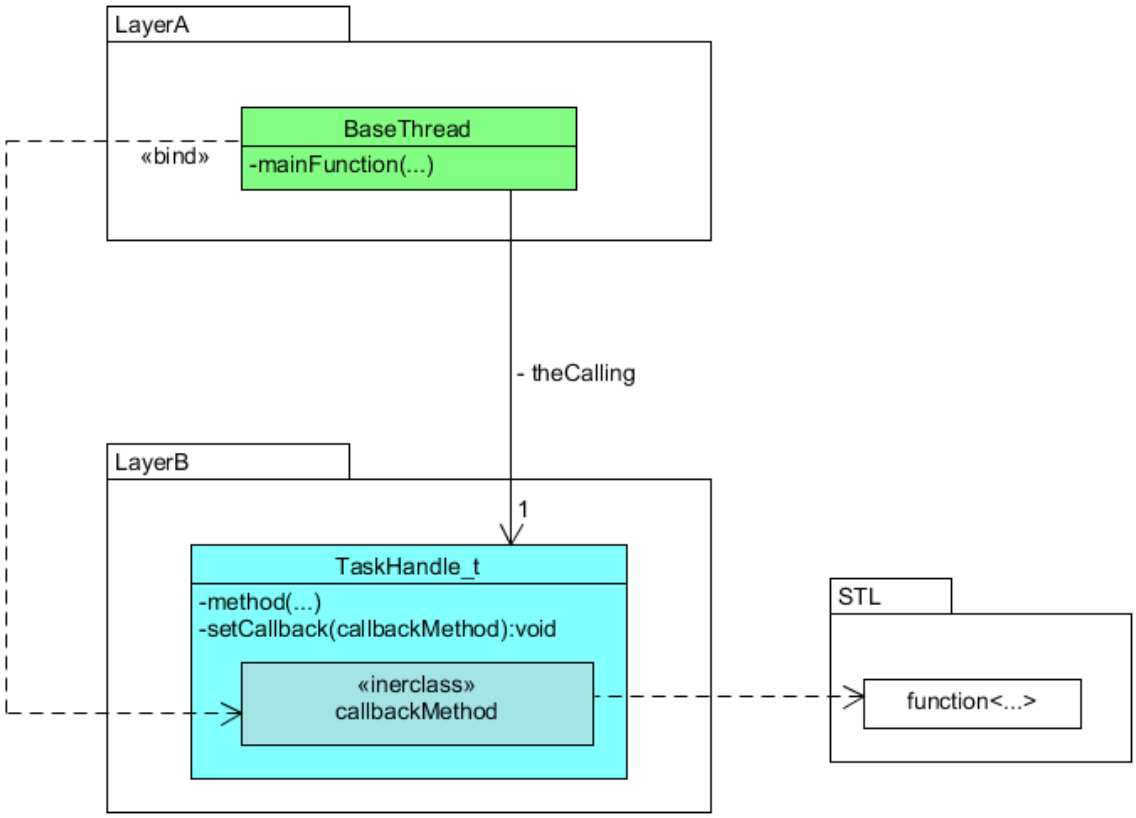


Figure 23 : Implementation of callback method pattern in BaseThread

This implementation present real problems:

- It needs to use C++ classes, but TaskHandle_t is not a class. It is just a pointer to something that Free RTOS names a task.
- It needs to implement functions on both classes. But TaskHandle_t is an internal "pseudo-class" of Free RTOS and same if it is possible to change the Free RTOS code it is not the goal of this work.

For those reasons, this solution was not adopted.

Using a void pointer to the BaseThread

The Free RTOS main function of the thread offers the possibility to use a void* parameter (pvParameter). The particularity of a void* pointer is that it can point on everything (same a C++ object). This parameter is set in the creation of the Free RTOS task.

It is also possible to have a static member function (the Wrapper) that get a pointer to a thread and call the main function of this thread (The function threadMain() in the present case).

The Figure 24 explains that in a set of diagrams.

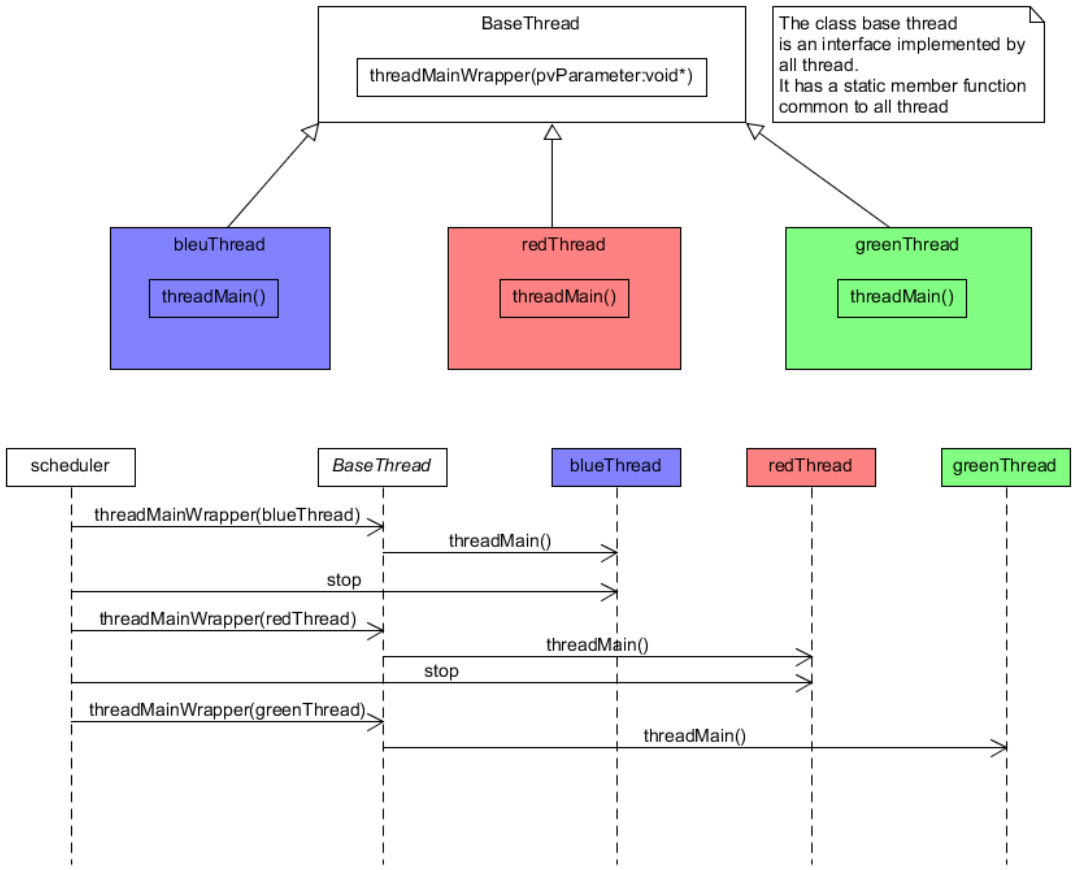


Figure 24 : The thread main wrapping

To resume, when the BaseThread subclass is created, it calls the Free RTOS function xCreateTask() and set, for pvParameter, a pointer to itself (`this`). And then, when the scheduler executes a task it is the good mainThread() method that is called.

This method is the one recommended by the FreeRTOS developers. It has been chosen for the implementation of the XFOS.

ITimer

ITimer is a class that manages Free RTOS software timers. It offers the possibility to implement timers that call a function (the timer callback function) when they expire.
The timer callback function is pure virtual, the user must implement it in a child class.

Normally, if the XFOS is used correctly, the user does not need to use this abstract class, if he wants a timer he only needs to use Events with a delay.

The Figure 25 present the class diagram of ITimer.

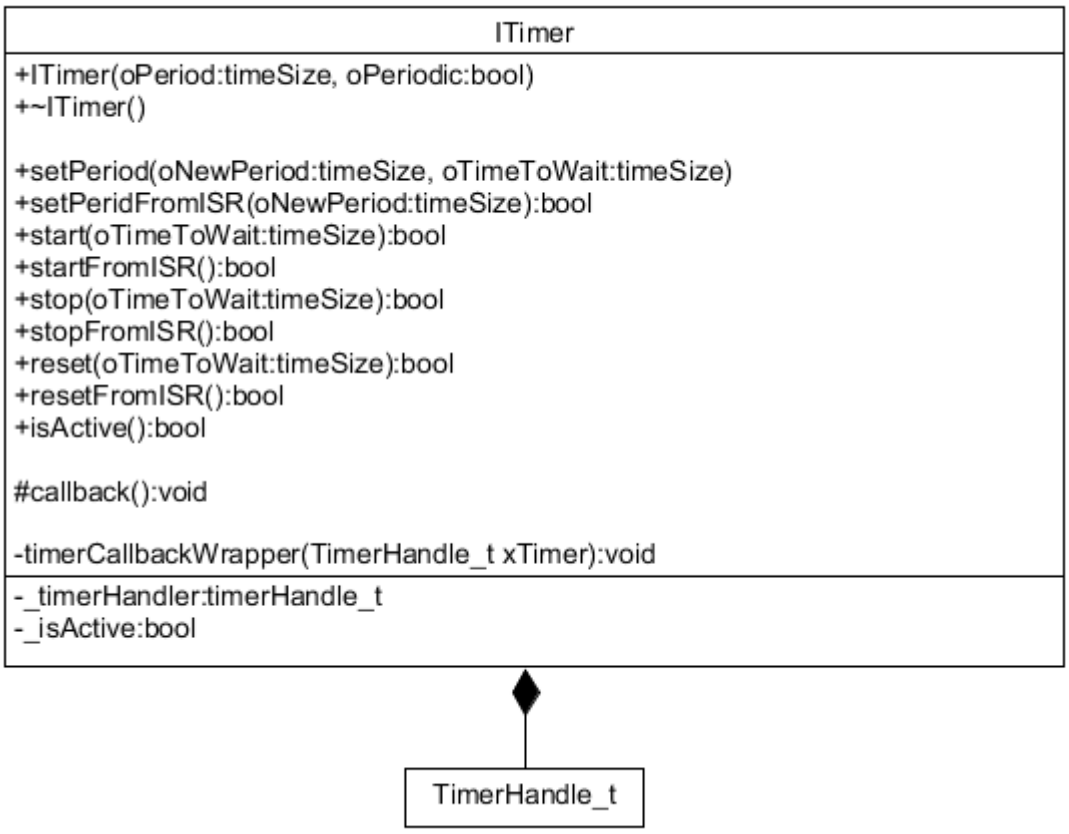
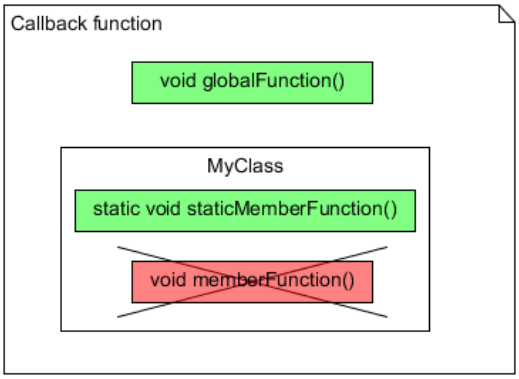


Figure 25 : Class diagram of ITimer

TimerCallbackWrapper

The Free RTOS timers already offer the possibility of call a callback function when they expire. But the callback function of Free RTOS timers is just a simple C function that can be called from everywhere.
In C++, the callback function should be an internal method of the class and should be able to be different in every subclass.



The problem here is the same as for BaseThread. It is that Free RTOS timer callback function needs to be a function with "C" linkage, this can be a static member function, or a global function.

It could not be a simple member function.

Figure 26 : Possible callback functions

The solution used is the same as the one used in BaseThread (c.f BaseThread for more information) but with a subtle difference.

With the BaseThread, the parameter of the main function was a void* pointer. It could also get everything as parameters. But for timers the callback function has as parameter a pointer to the timerHandle_t that expire so it is not possible to access to the ITimer with it (Figure 27).

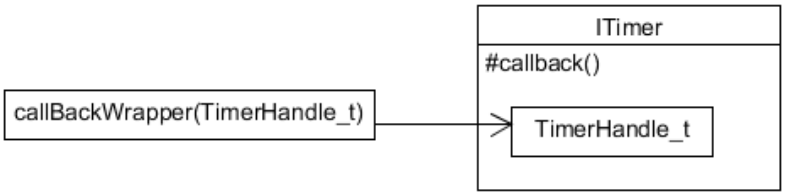


Figure 27 : Work of Free RTOS callback function

The better way for work is presented in Figure 28.

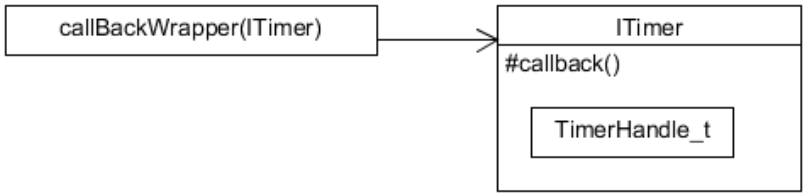


Figure 28 : Better work for callback

This option is not possible because it implicates to modify the Free RTOS source code.

This solution is located in the analysis of the functionxTimerCreate (Figure 29).

```
TimerHandle_t xTimerCreate
                  ( const char * const pcTimerName,
                    const TickType_t xTimerPeriod,
                    const UBaseType_t uxAutoReload,
                    void * const pvTimerID,
                    TimerCallbackFunction_t pxCallbackFunction );
```

Figure 29 : Definition of xTimerCreate

Software timers could have an ID that is a void*, and luckily the software timer API has also a function to get the id of a timer (Figure 30) this get as parameter a TimerHandle_t exactly what we receive as parameter for callback function.

```
void *pvTimerGetTimerID( TimerHandle_t xTimer )
```

Figure 30 : Definition of pvTimerGetTimerID

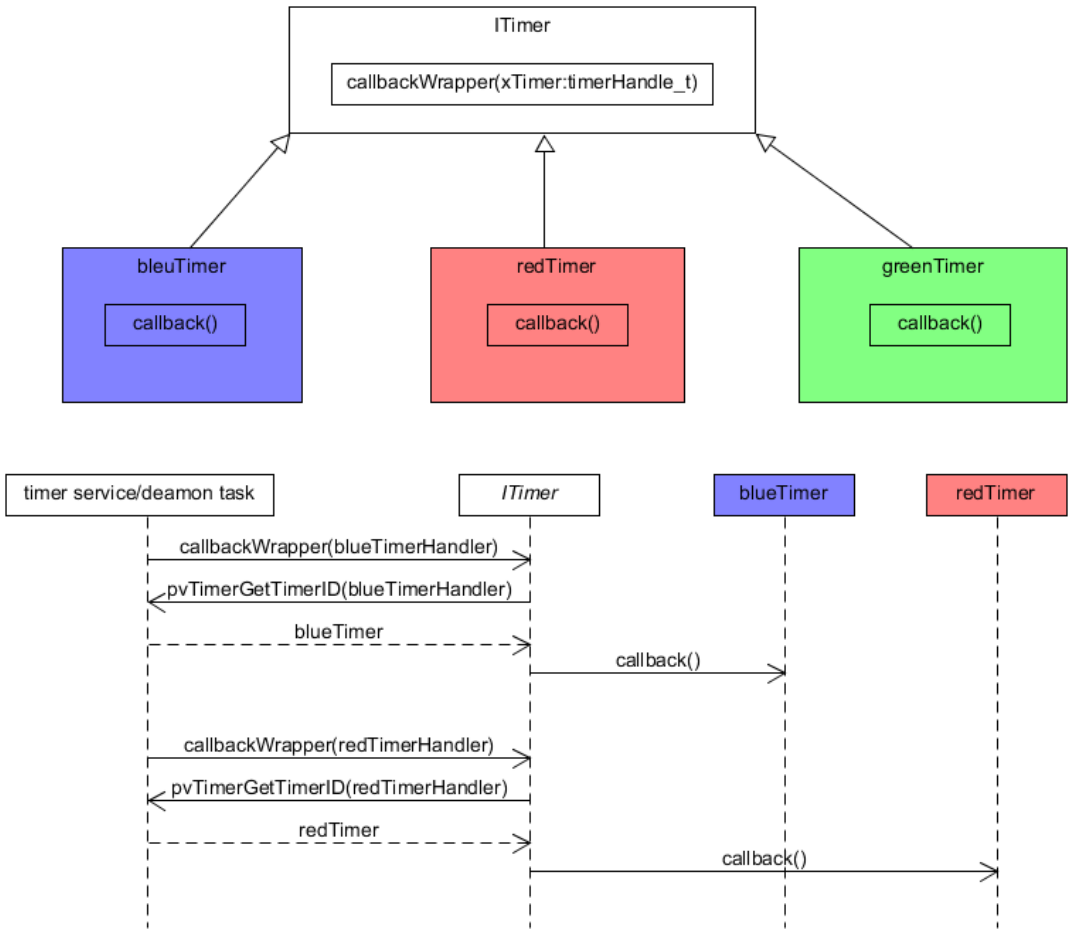


Figure 31 : The timer callback wrapping

5. XF package

The XF package contains all classes that don't need to be reimplemented if another OS is used. Those classes are the interface with the user application, therefore they must never change their interface.

Thread

This class is the specific class that make the XF works. It contains the event queue and the event dispatcher. So, it is this class that processes state machines.
It also determines if an event needs a delay and calls the timer manage if yes.

Thread inherits all Free RTOS function from BaseThread.

The Figure 32 presents the class diagram of Thread.

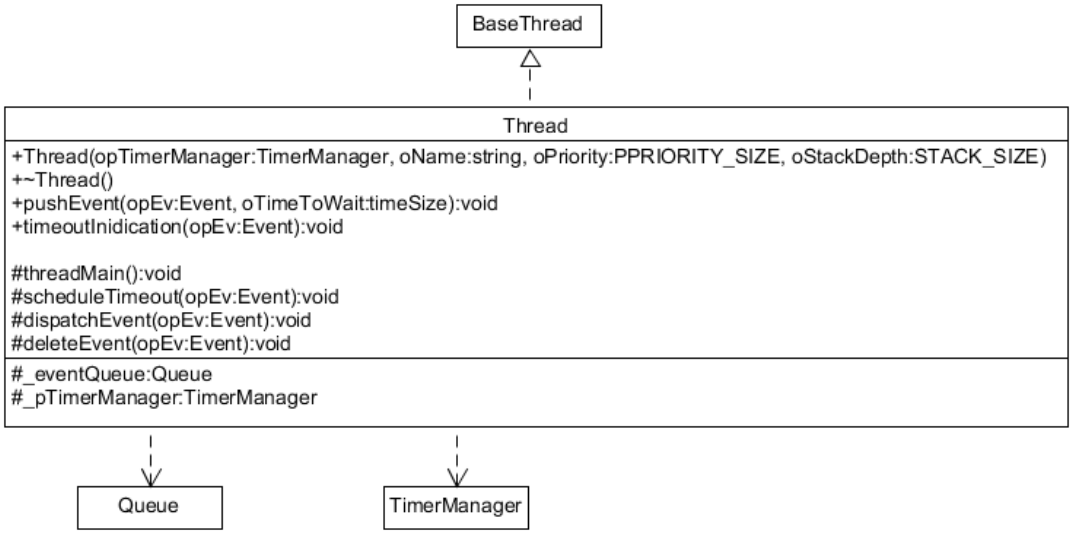


Figure 32 : Class diagram of class Thread

TimerManager

The timer manager is used to manage events that need a delay. It offers to thread the possibility to start a timer and to be informed when this one expires.

It exists 2 solutions for the timer management:

- Use the same method as the ECSG XF
- Use Free RTOS timers

ECSG XF method

This method is described in detail in chapter IV, it consists of use a list of special timers that will be managed by one Free RTOS timer. The Free RTOS timer will update the list every time he expires.

This method works perfectly, but it presents some inconvenient:

- It needs the implementation of others software timers, which is unnecessary because Free RTOS already offers these.
- It implements a list of timers in the timer manager. Which takes place uselessly because Free RTOS can already manage its timers in a list.

Conclusion, this method is very interesting when the XF is used as an IDF (without operating system) but it is not the most effective when an OS is used.

In a first version of the XFOS, this solution has been used. The source code could be found in the package depreciated.

Use Free RTOS timers

This solution proposes to use the timers of Free RTOS (ITimer) as delay for the events. With this method, the timer manager just becomes an interface that creates timers when a thread needs it and notifies this thread when the timer expires.

This Figure 33 shows how it works.

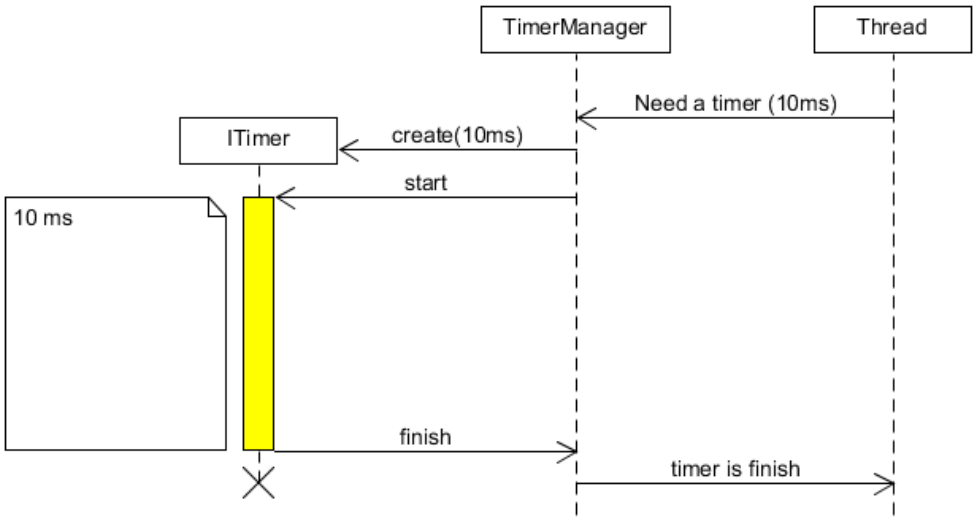


Figure 33 : Working of timer manager with Free RTOS timers

This Principe of operating is simple to understand and easy to implement. Moreover, it uses only some OS resources.

This solution is the final solution chosen for the XFOS. The Figure 34 presents the class diagram of this solution for the timer manager.

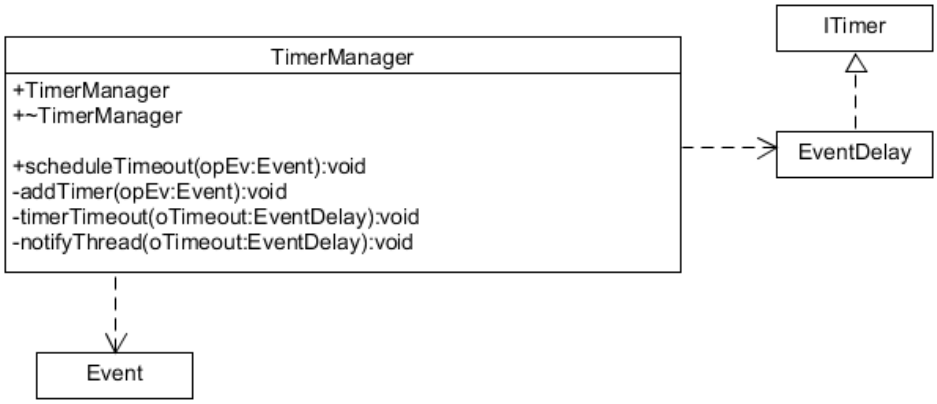


Figure 34 : First class diagram of TimerManager

Put the timer manager in an independent thread?

At the beginning of the project the possibility to put the timer manager on its own thread was proposed. This section presents why this proposition was not retained.

A thread needs resources

Create a thread needs some resources from the OS:

- It needs space for the stack that could be used for a user thread.
- Since it needs to communicate with other threads, it needs a queue to put requests or commands from threads.
- The usage of a queue implicates to implement a class “Request” that will ask the timer manager to make a specific action (add a timer, notify a thread when a timer expire).

Wasting time

The timing management in the XFOS is already not optimal. In fact, the real time used to process an event with delay is bigger than the delay specified in the event. The Figure 35 shows where this time is lost.

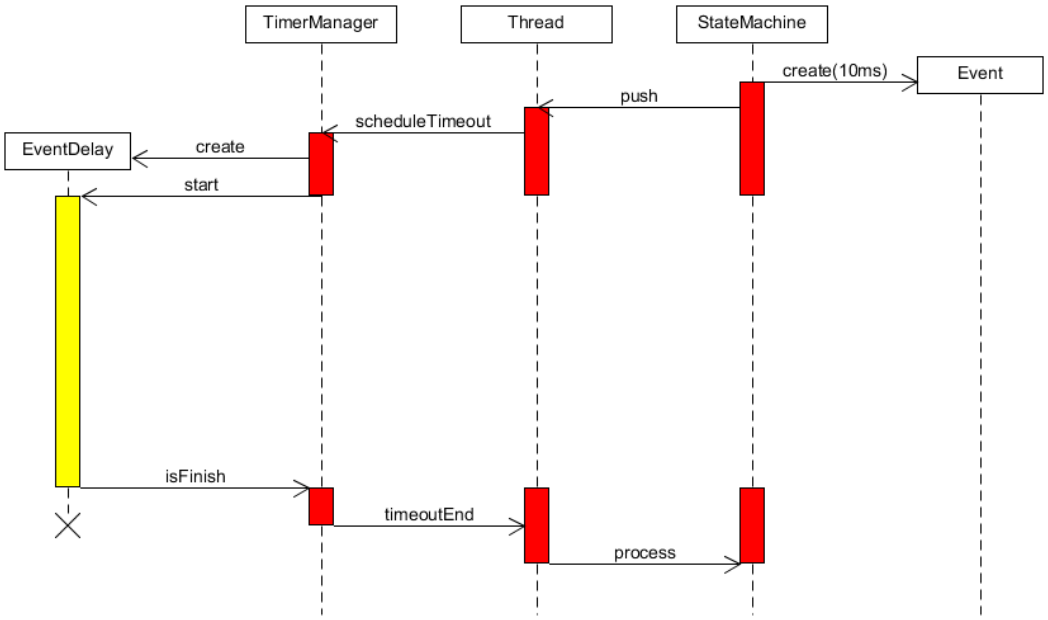


Figure 35 : Time wast during the processing of an event with delay

Red parts show the time lost during the processing of an event with delay. The yellow part is the effective delay time.

Using the timer manager in an independent thread will further extend this wasted time as shown in the Figure 36.

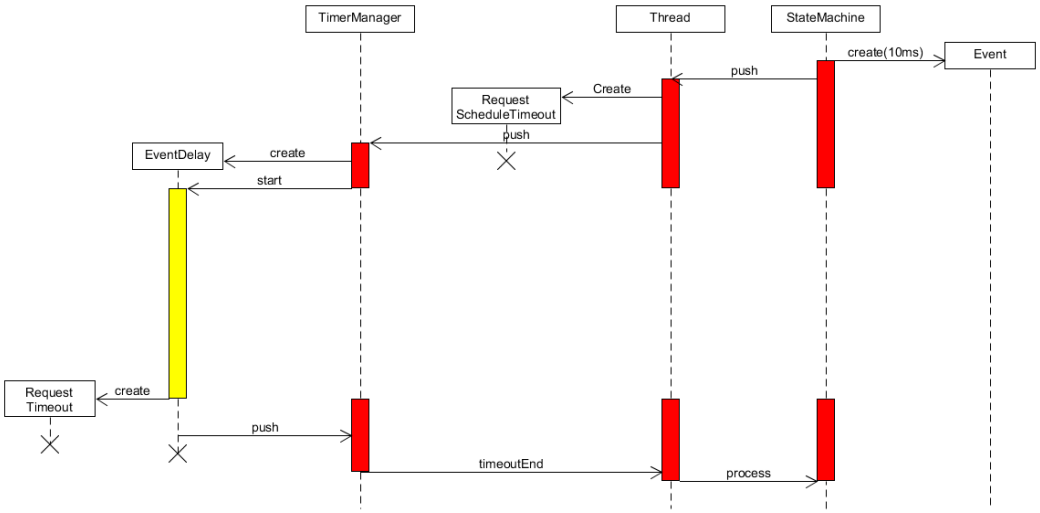


Figure 36 : Time waste when timer manager is in a separate thread

Final solution

The final solution of the timer manager is a modified version of the solution 2 (use Free RTOS timer) it is a set of functions called by threads, so it does not run in a separate thread.

The difference with the second solution is that the timer manager implements finally the singleton pattern. This choice was made because the it is not necessary to have 2 instances of the timer manager in the XFOS.

The Figure 37 present the final class diagram in the TimerManager.

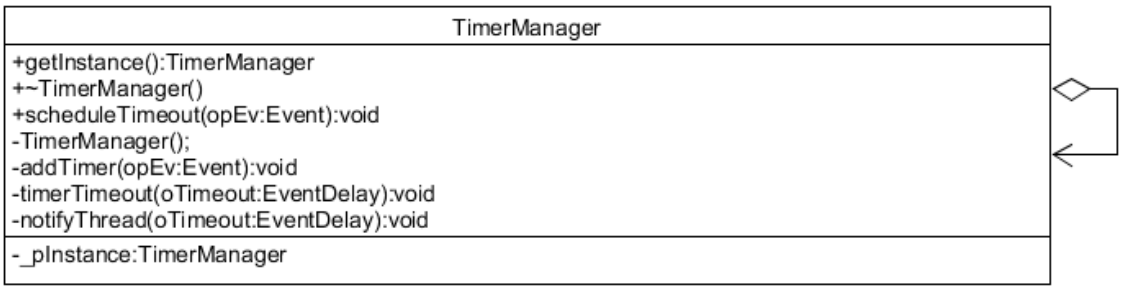


Figure 37 : Final class diagram of the TimerManager

Event

Event is the one of principal class of the XFOS. Events are used by state machines to execute themselves. This class do not manage the part of the delay it just has the information but it is TimerManager, EventDelay and Thread that handle this part.

The class event just contains information about its processing such as, the destination state machine and the destination Thread, the delay before processing and the type of the event. Event has also an ID that identifies it.

Events are created directly by the state machines, but they are deleted by the event dispatcher in the thread.

The Figure 38 presents the final class diagram of the Event.

Figure 38 : Class diagram of Event

The ID of events

The ID of events is automatically generated during its creation. The strategy used to implement this part is the simplest. A static variable nextFreeID is used. When an event is created, the nextFreeID is set as the id of the new event, and its value is incremented.

This method is not the most secure because it does not ensures that 2 events will never have the same ID. Two events could have the same value when the variable overflows. Here if the event with the ID 0 already exists and a new event is created also 2 events with the same ID could live in the same time.
Despite this, the probability that the first event created already exists when the variable overflows is very low and using another solution, such as an ID manager that indicates which ID is free makes no sense because it need more processing time for something that does not pose a serious problem.

Static Events

A method to create static event is proposed. A static event is an event that is not destroyed after is has been processed.

If the user wants to use a static event he needs to define a specific value for de ID.

Event creation and destruction

As shown in the class diagram of the Figure 38, the constructor and the destructor of events are private and static functions createEvent() and deleteEvent() are used to create and delete Events. This was done because the operation of the XFOS needs dynamically created events.

When the user calls createEvent(), a new event is dynamically created. Then function deleteEvent() will not directly delete the event. It just will put the attribute isActive to false (this is the same work as cancel). When an event that is not active is dispatched by a thread it is not sent to its state machine, it is directly deleted by the thread (the class Thread is friend with the class Event so it can access private members).

The Figure 39 presents the live cycle of an event and the Figure 40 present the live cycle of a canceled event, finally the Figure 41 shows the life cycle of a deleted event.

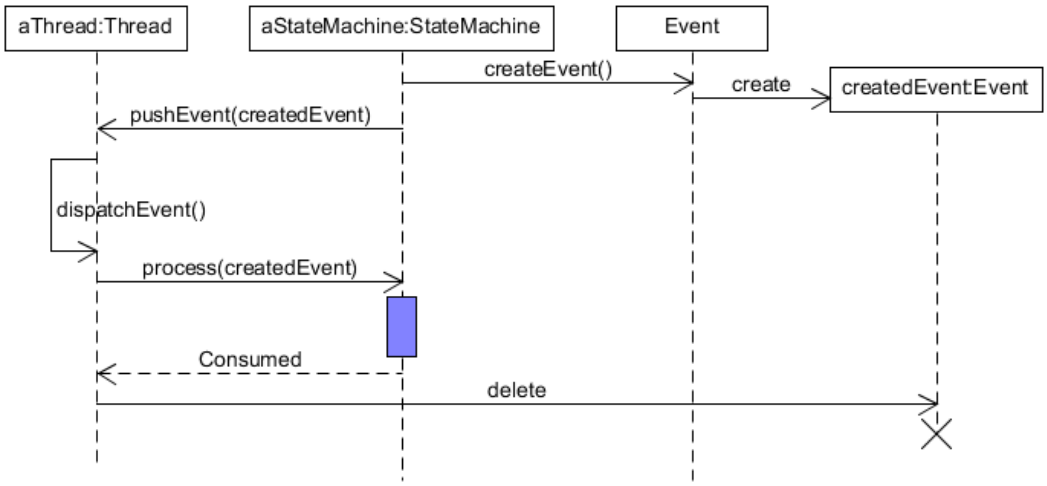


Figure 39 : Life cycle of an event

Here the event is processed by the state machine before being deleted.

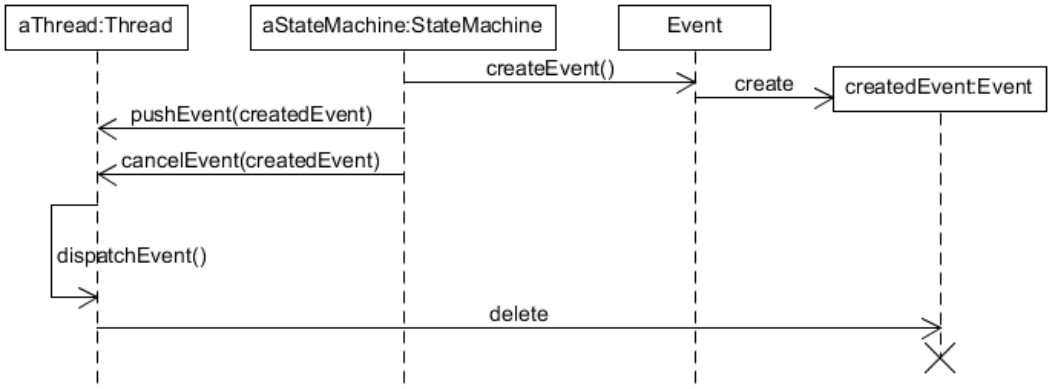


Figure 40 : Life cycle of a cancelled event

Here the event is directly deleted.

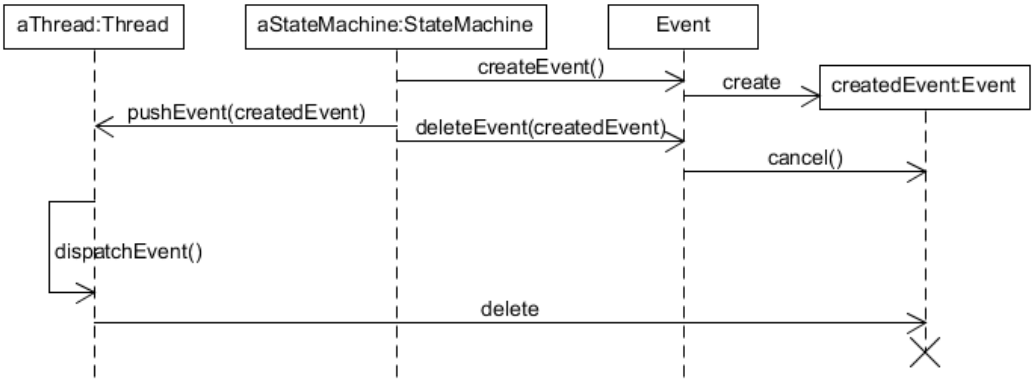


Figure 41 : Life cycle of a deleted event

EventDelay

EventDelay is a sub class of ITimer it is a timer created by the timer manager. As its name says, this class implements the delay of an event.

When an EventDelay ends, it contacts the timer manager.

The Figure 42 presents the class diagram of the EventDelay.

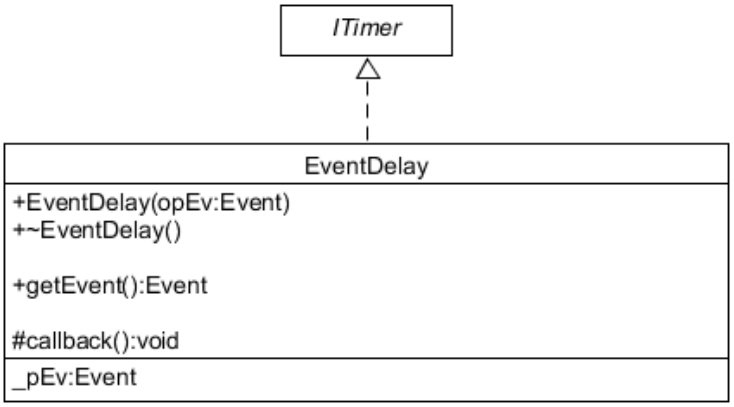


Figure 42 : Class diagram of EventDelay

IStateMachine

This class is the interface of state machines for all other classes of the package. It is used in Thread and events. It contains all the primary function used by the XFOS to interact with state machines.

This class is only an interface, it means that it is a pure virtual and its methods must be reimplemented in sub-classes.

The Figure 43 shows the class diagram of IStateMachine.

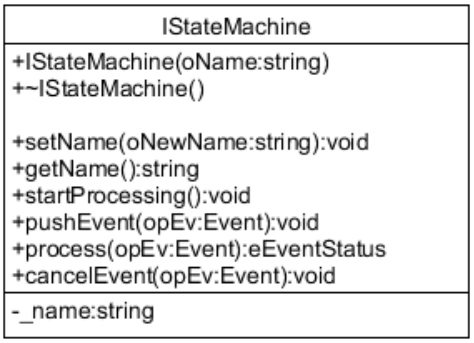


Figure 43 : Class diagram of IStateMachine

All methods of this class are pure virtual except setName() and getName().

StateMachine

This class inherits form the interface IStateMachine. It is the skeleton of state machines, it implements all functions needed by state machine for work correctly, but it is also a pure virtual class because the function that will process the events is not implemented.

The class diagram of Figure 44 shows all methods and attributes of StateMachine

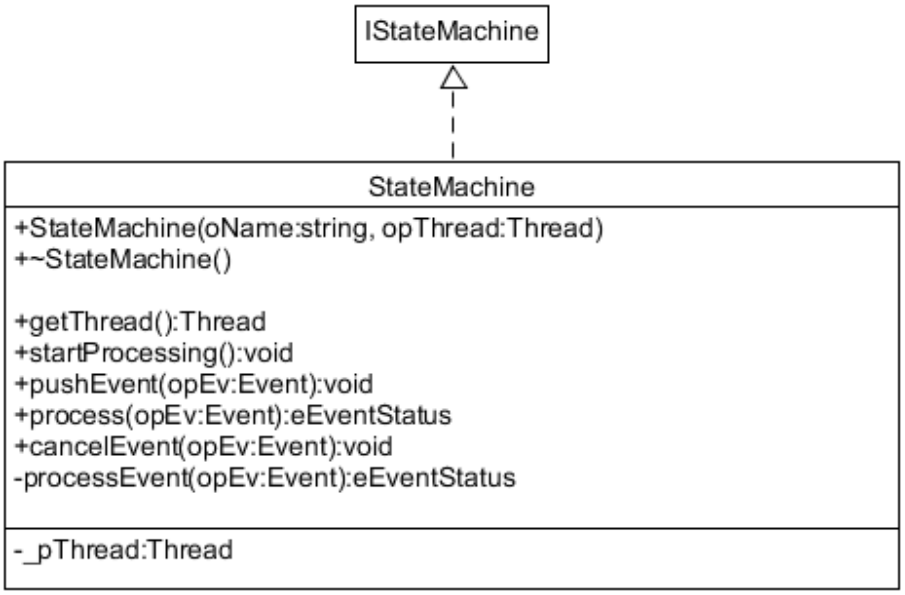


Figure 44 : Class diagram of StateMachine

ErrorHandler

The class ErrorHandler implements the class BaseThread. It is a thread with a higher priority than user threads. Its work is to process an error if one occurs.

The ErrorHandler is an abstract class. It is the work of the user to implement what to do if an error occurs.

ErrorHandler implements the pattern singleton because only on instance of it must exist in the XFOS.

The Figure 45 present the class diagram of the class.

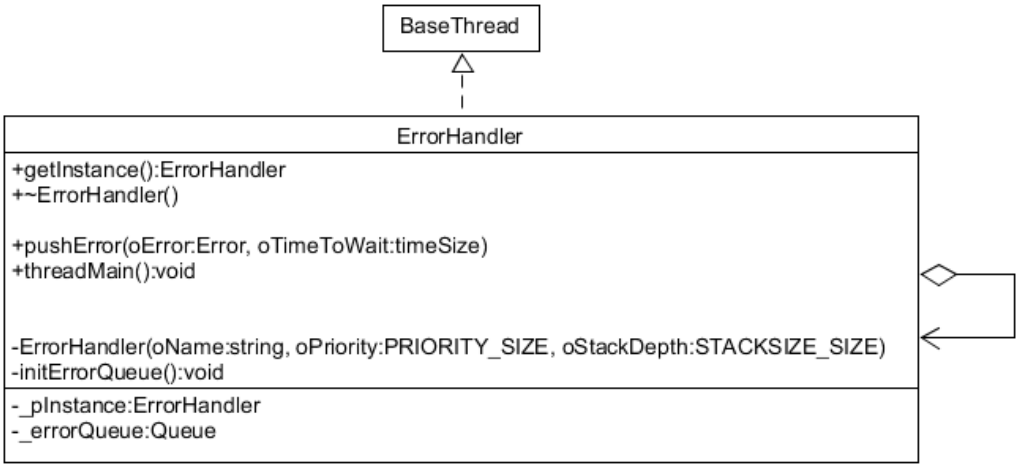


Figure 45 : Class Diagram of ErrorHandler

Error

An error is sent when something does not work as expected. An error indicates the nature of itself and its severity.

It exists 4 levels of priority.

Priority level	Meaning
LOW	The error is not critical for the work of the system
MEDIUM	The error could generate a bad work
HIGH	The system will not work correctly and could fail
VERY HIGH	The system fails

Table 5 : Error severity

The class diagram of the Figure 46 presents the class error.

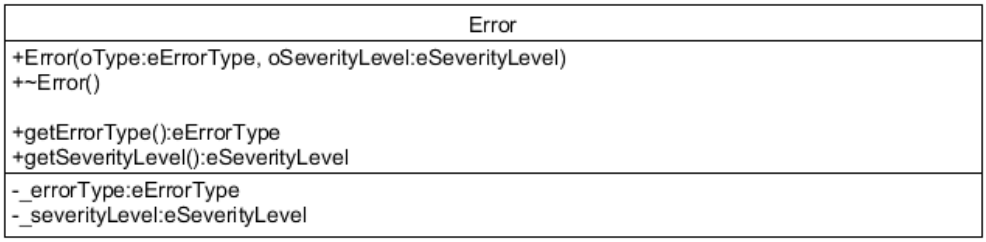


Figure 46 : Class diagram of Error

VIII. Tests

The specification of the project says that the test should be made with Google test. But this API was not adapted to a bare metal system (A system without OS), it is only usable with an operating system such as Windows or Unix. The study of the Google test's code is presented in the chapter IX : Google test code analyse.

To ensure the proper work of the system a set of tests has been developed.

The package "tests" contains files for all tests executed for the XFOS.

1. Normal event processing test

This test proves the proper processing of a normal event (an event without delay) it also demonstrates the proper functioning of thread, Queue and state machine.

In this test, a Thread "nepThread" will dispatch and process simple events to a StateMachine's subclass "NEPStateMachine" this state machine will just toggle a pin on the board.

The NEPStateMachine sends it state in the UART via the serial RS-232 communication protocol. Thread will also indicate its principal actions.

The Figure 47 shows how the event is processed in this test.

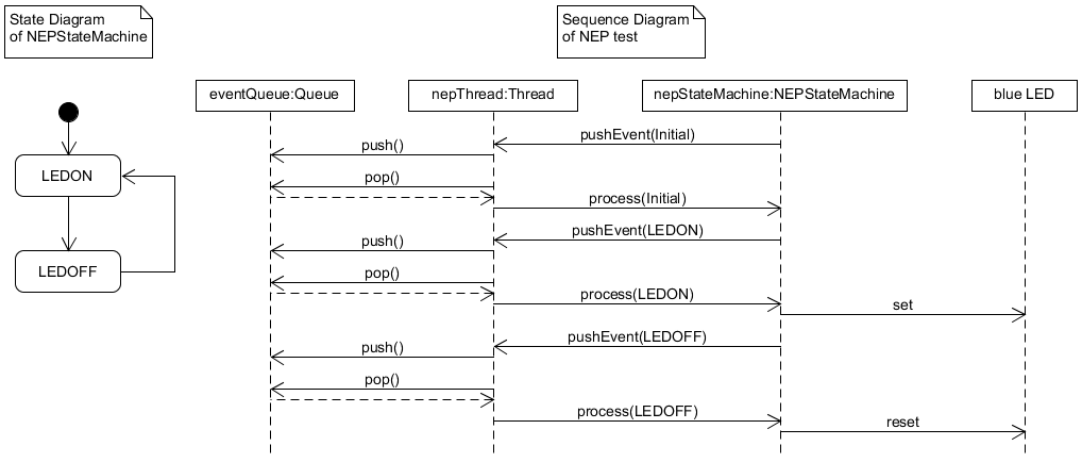


Figure 47 : Normal event processing test

Result

The Figure 48 presents the result received via the serial port.

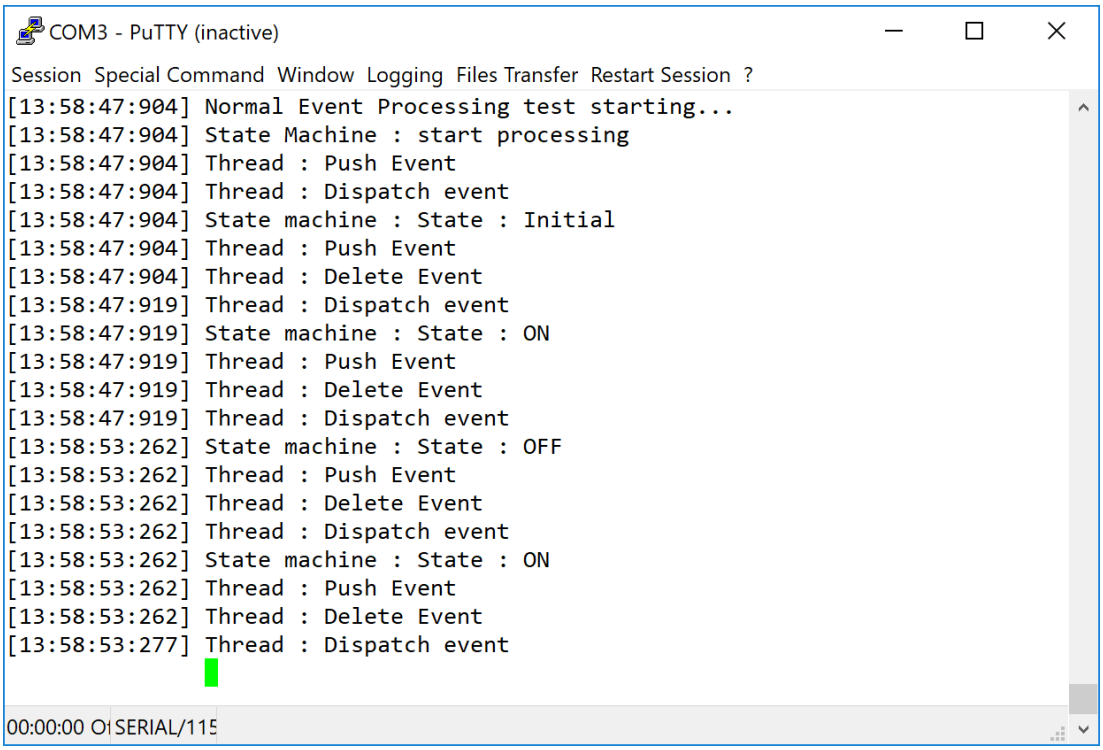


Figure 48 : Result of Normal Event Processing Test

As shown in the Figure 48, at the beginning of the test, the state machine sends the event Initial by calling "startProcessing()". The Thread pushs it in the event queue and after dispatches it. In the initial state, the state machine sends the custom event to begin its next state. The custom event is pushed in the queue by the Thread. After that, the Initial event is deleted and the custom event is dispatched.

6. Delay event processing test

This test check if an event with delay is processed correctly in the XFOS. It also demonstrates that the timer manager and EventDelay work correctly.

This test is very similar to the normal event processing test, but it presents a little difference. The StateMachine sub class sends events with a delay of 250 ms and toggle the blue LED of the board. With this delay the LED blinks enough slowly so that the human eye can see him.

In this test, the state machine indicates its actual state via the UART. Thread and TimerManager send their principal actions.

The Figure 49 shows state chart of the state machine DEPStateMachine.

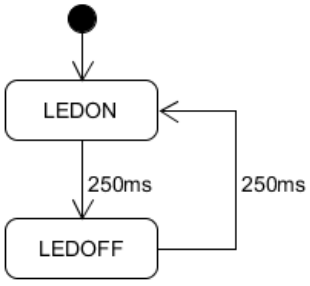


Figure 49 : State chart of DEPStateMachine

The sequence diagram of the Figure 50 shows steps of the processing of the event.

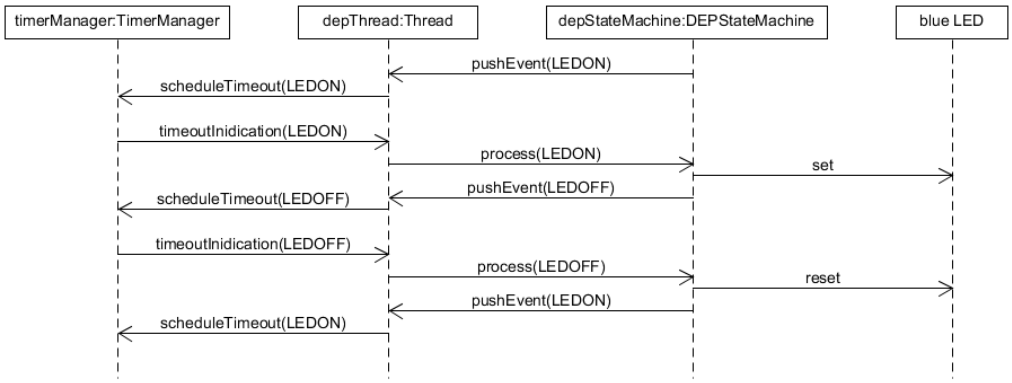


Figure 50 : Delay event processing test

Result

The Figure 51 presents the result of the test.

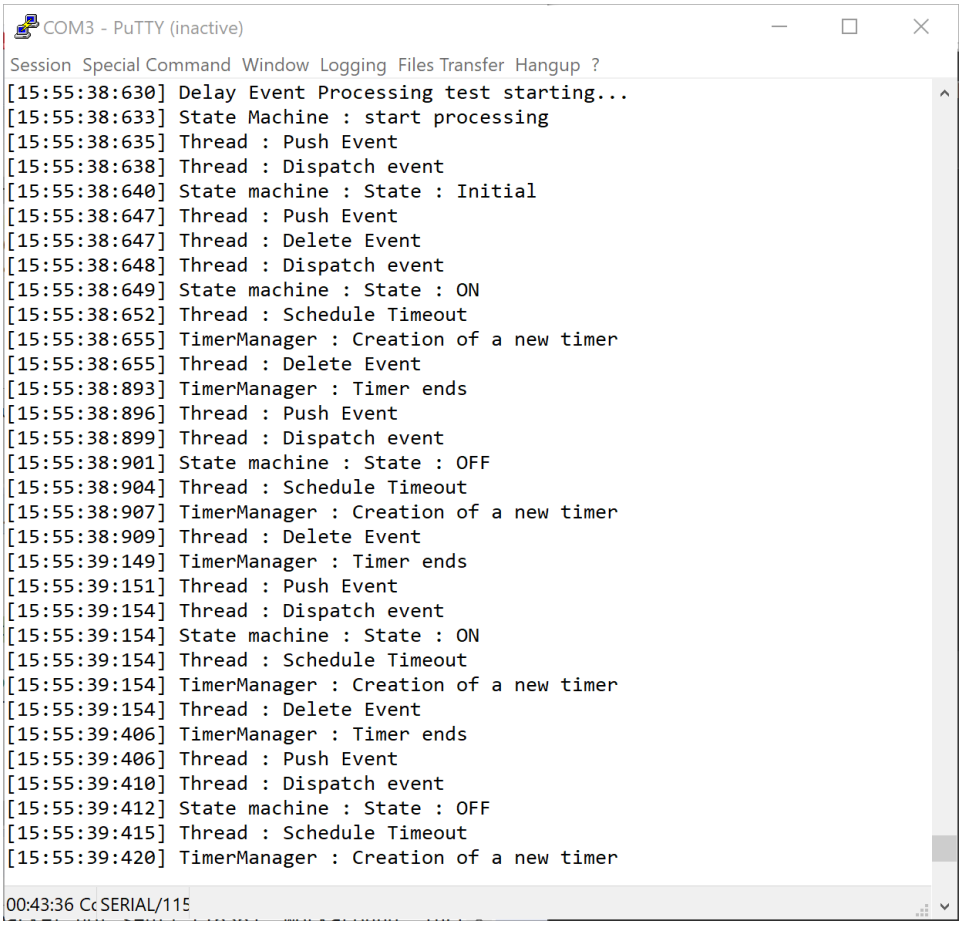


Figure 51 : Result of the Delay event processing test

This image shows that the events are not directly pushed in the queue, the thread schedules a timeout and the timer manager creates a timer, after the specified time, the timer manager indicates that a timer ends and the thread push an event in the event queue.

If the time between the creation of a timer and the timer's end is checked it is possible to see that the time is not of 250 ms, it varies between 238 ms and 252 ms.
This problem is studied and explained more precisely in the section 14 of this chapter.

7. Cancel event test

This test will check if the “cancel” of an event works correctly. In this test, a state machine will light up the blue LED, after 250 ms it will light up the red LED, after 250ms it will light up the orange LED. In this state, the state machine will send two events, the first one is used to light up the green LED and will terminate the state machine, it is send with 250ms of delay. The second one is a timeout that will put the state machine to the BLUELEDOFF state.

Normally, the event that lights up the green LED is canceled so the green LED must never light up.

To know if this test works just see if the green LED lights up, if yes, cancel event does not work correctly.

The Figure 52 shows the state machine of this test.

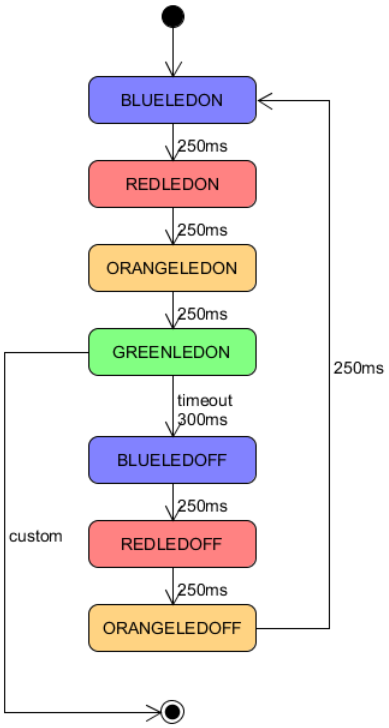


Figure 52 : State machine of Cancel event test

Result

The state machine sends its state on the serial port every time it changes its state. The Figure 53 shows the result of the test.

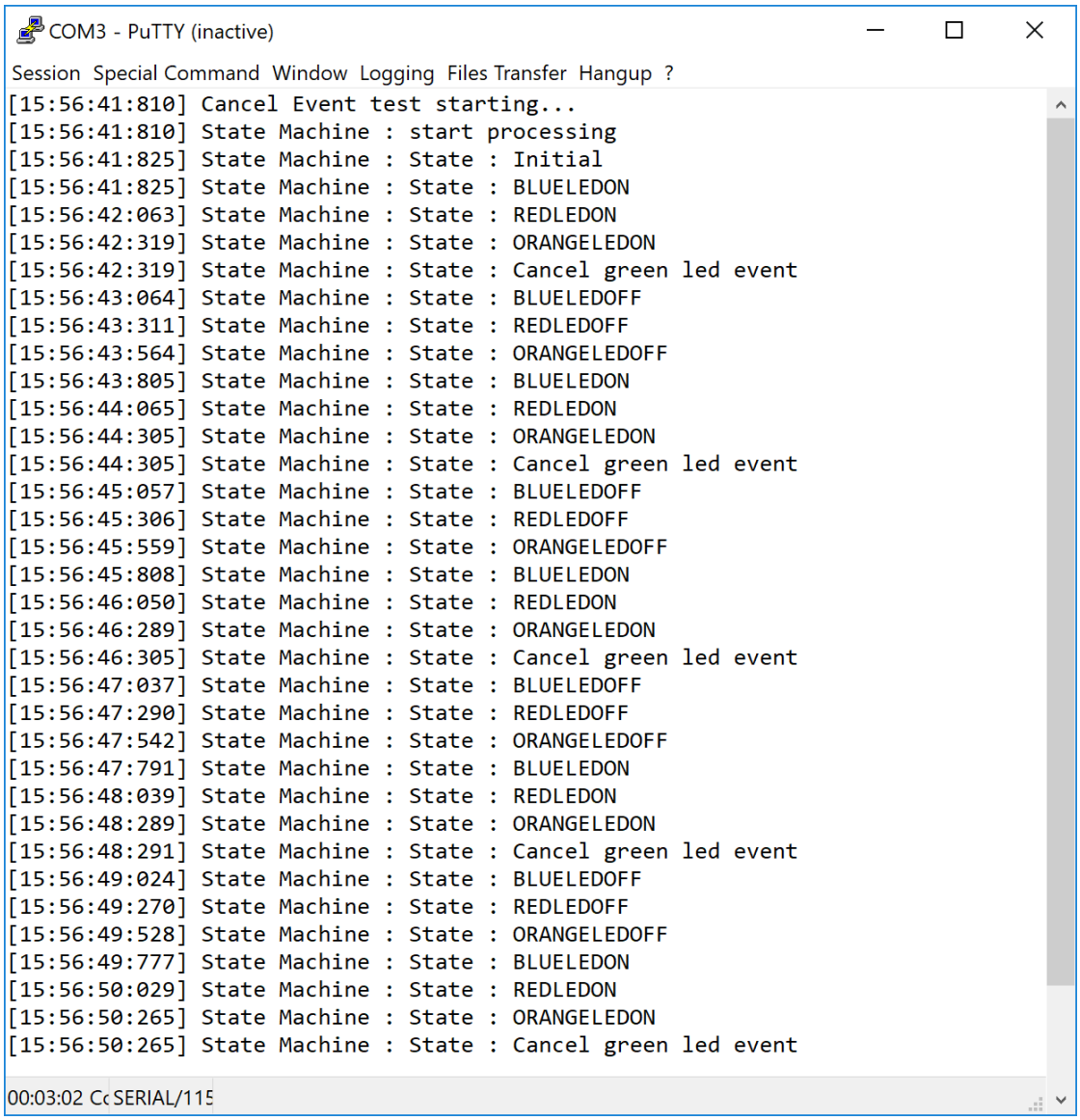


Figure 53 : Result of cancel event test

The state GREENLEDON never appears and the BLUELEDOFF state follows the Cancel green led event, it means that cancel event works.

8. Multi state machines Mono thread test

In this test, four state machines will be created in one thread. All of them will just toggle one of the four LEDs of the board. The delay of the blink is 250ms. The processing of an event is very fast, so, for a human eye, this four LED will normally blink at the same time.

The Figure 54 presents the state diagram of all state machines.

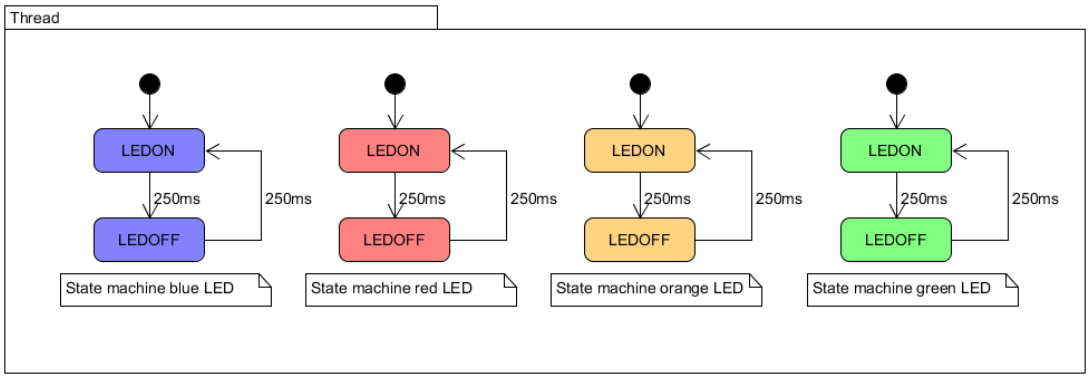


Figure 54 : State machines of multi state machine mono thread test

Result

All state machine sends their actual state in the UART. The Figure 55 presents the result received in the serial port.

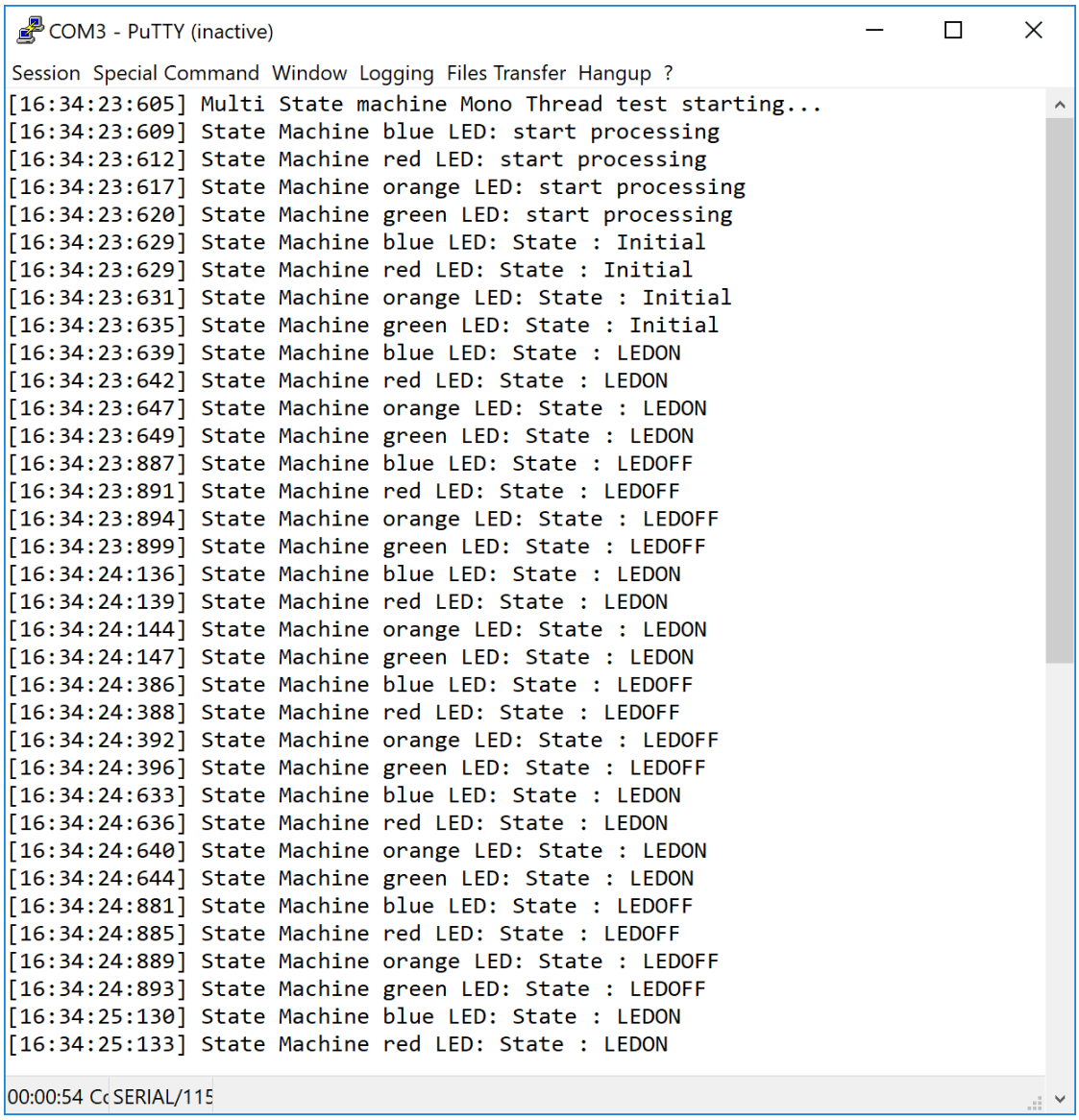


Figure 55 : Result of multi state machine in mono thread test

The state machine blue is the first one that starts processing, also it is always the first one that changes its state.

The test works as expected and proves that many state machines could work in the same thread.

9. Multi state machine Multi thread test

This test is like the multi state machine mono thread. But this time all state machines are in different threads. If everything goes right, the four LED will blink at the same time.

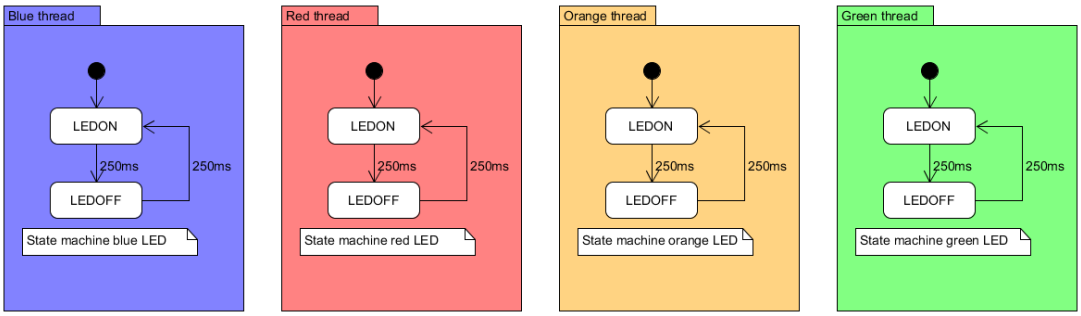


Figure 56 : : State machines of multi state machine multi thread test

Result

The Figure 57 presents the result of the test received in the serial port.

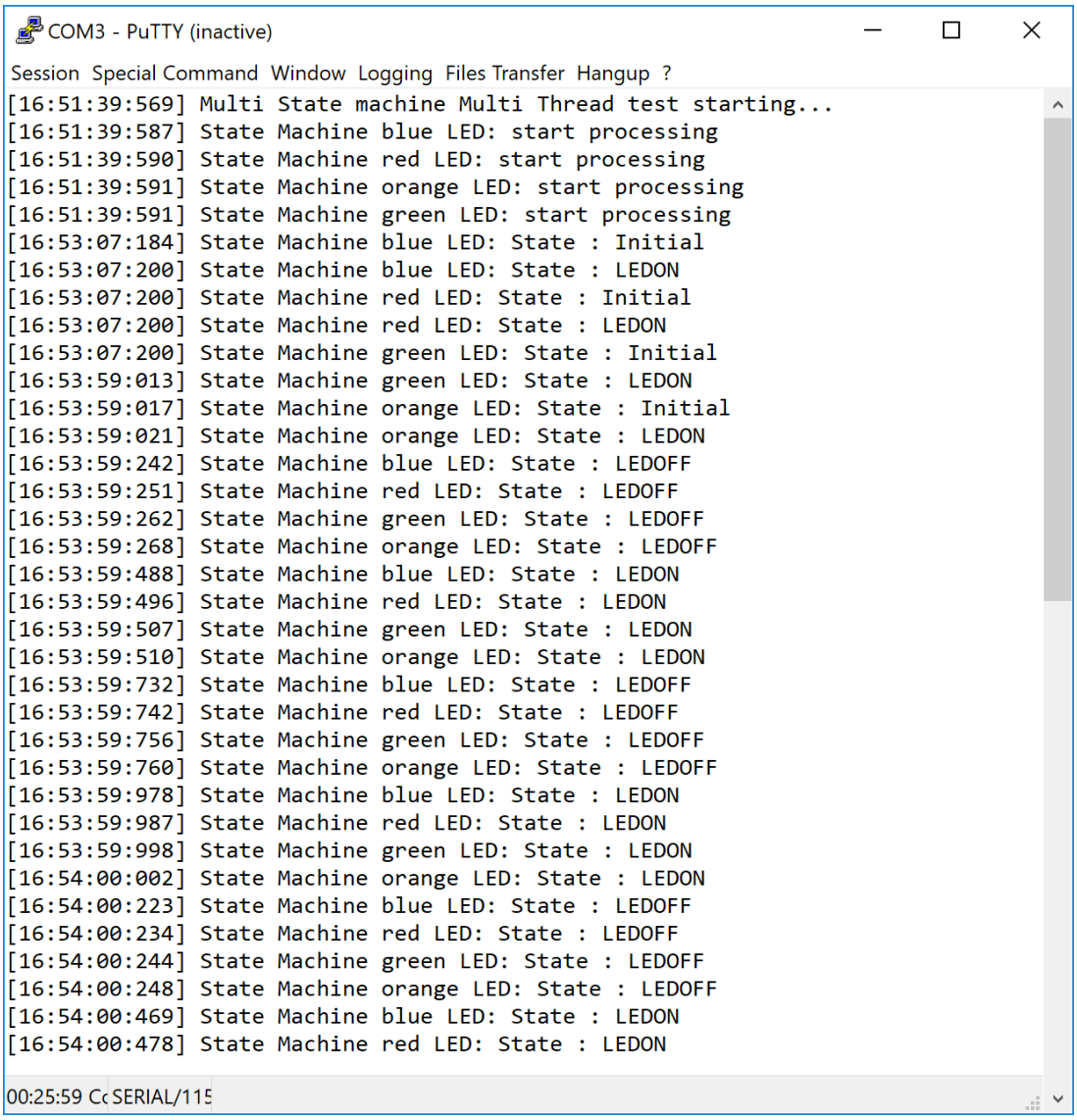


Figure 57 : Result of multi state machine in multi thread test

This result presents some differences with the last one, particularly at the beginning. In the last test, all state machines become in their initial state before the state machine blue starts the LEDON State. In this test, the state machine blue starts the LEDON state before the state machine red entres in its Initial state. This difference is due to the fact that there is no delay time between Initial state and LEDON state. The thread of the state machine blue goes in the waiting state only after the state LEDON because the event sent in this state has a delay of 250 ms. Also, when the thread tries to pop an event from its event queue, this one is empty.

10.Inter-state machine communication

This test is separate in 2 parts. In a first step two state machines will communicate in a same thread. In the second step, the same two state machines will be put in different threads.

In this test, two state machines will communicate. The first one manages the blue LED. It will light up the blue LED, after that it will send an event to the second state machine this will light up the red LED and shut it down after 250 ms. Finally, the second state machine will send an event to the first one that will shut down the blue LED and restart a sequence.

The Figure 58 presents the state diagram of the test.

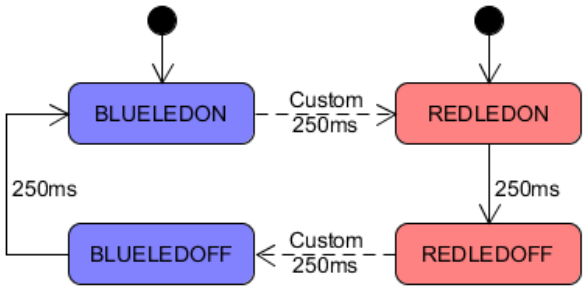


Figure 58 : State chart of inter state machine communication

Result

In the same thread

The Figure 59 shows the result received in the serial port when the two state machines are in the same thread.

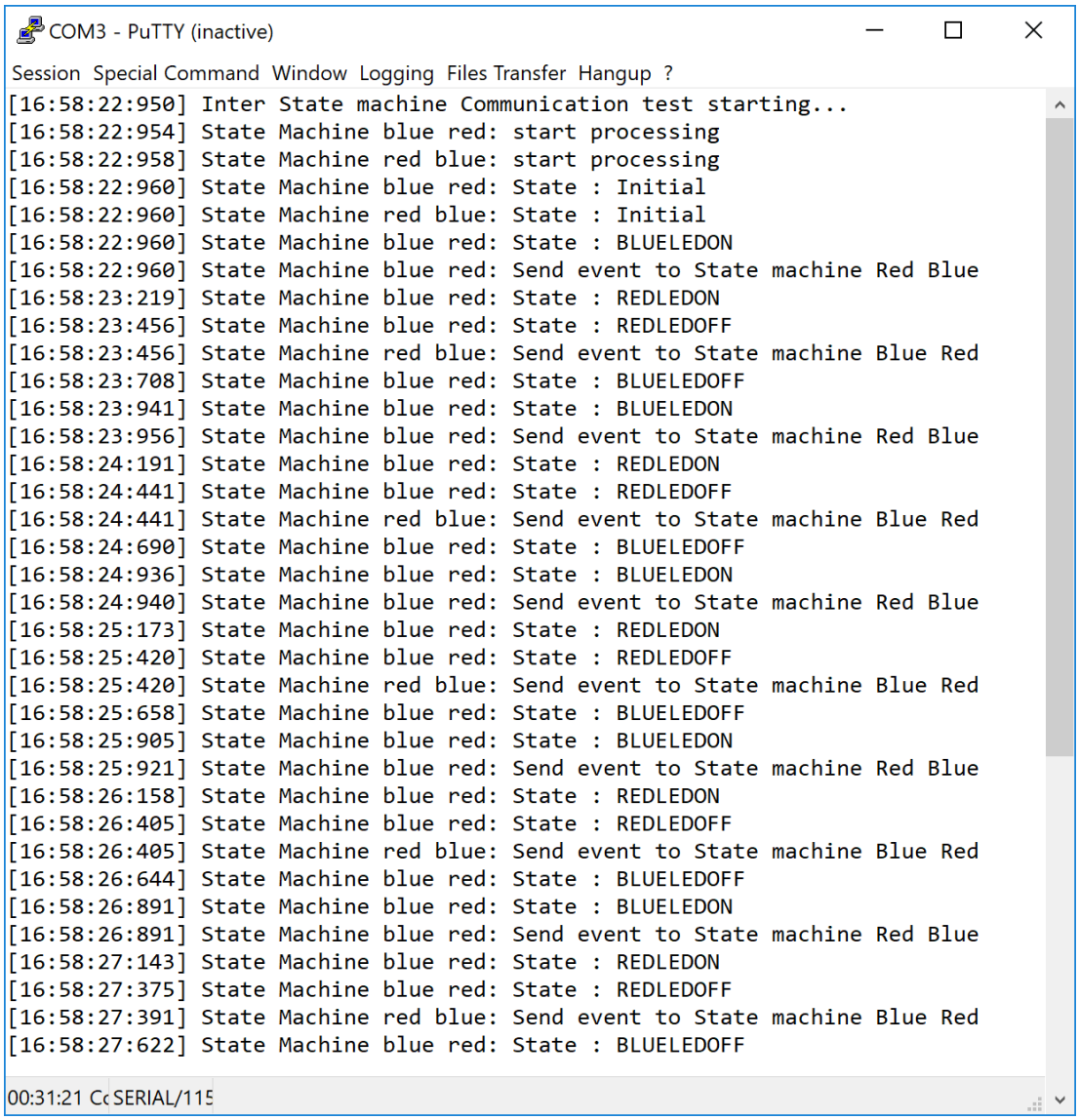


Figure 59 : Result of the inter-state machine communication in a mono thread test

Here the two state machines start their Initial state before the state machine blue enters in the BLUELEDON state. After that it sends an event to the state machine red that blink the red LED and sends an event to the state machine blue.

This test demonstrates the two state machines could communicate when they are in the same thread.

In different threads

Now the state machines are in different threads. The Figure 60 shows the result.

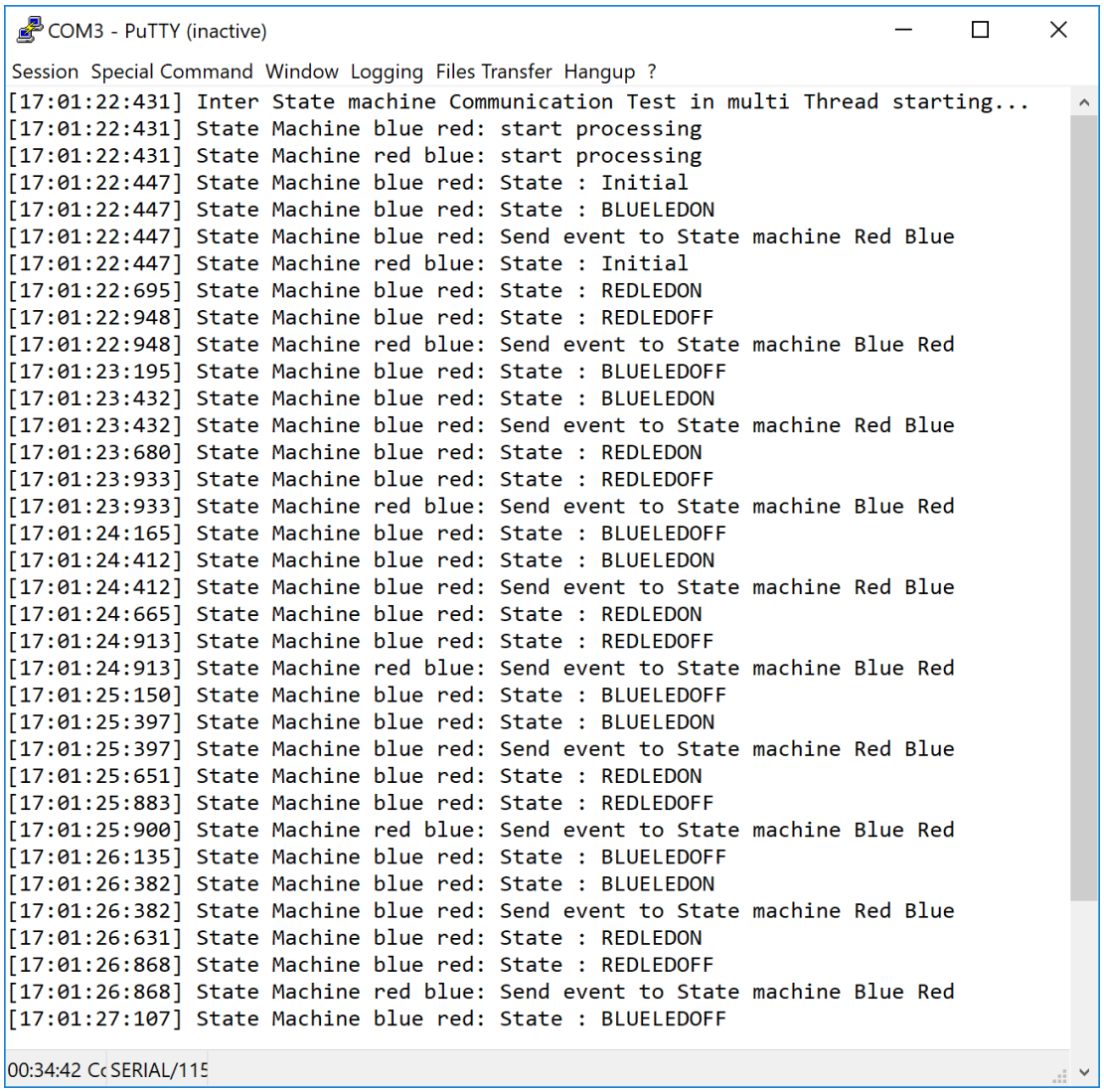


Figure 60 : Result of the inter-state machine communication in different threads test

Here it is the same scenario as the Multi state machine Multi thread test. The state machine blue starts the Initial and the BLUELEDON state before the state machine red starts the Initial state. The thread of the state machine blue falls asleep only when its queue is empty.

This test shows that state machines could communicate same in different threads.

11.Priority Thread

This test has been developed to ensure that a priority thread could work correctly. In this test, a thread with two levels of priority is created. It processes two state machines, the state machine blue led and the state machine red led. Both will blink a led but the state machine blue led sends events with higher priority than red led. It means that the events of the state machine blue must normally be processed before the events from the state machine red, as shown in the Figure 61.

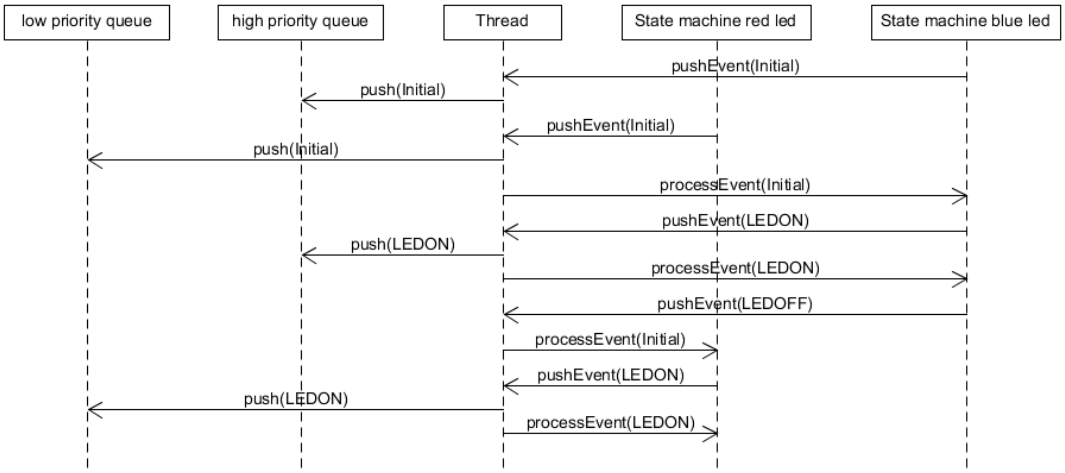


Figure 61 : Priority thread test

Result

The Figure 62 presents the result of this test.

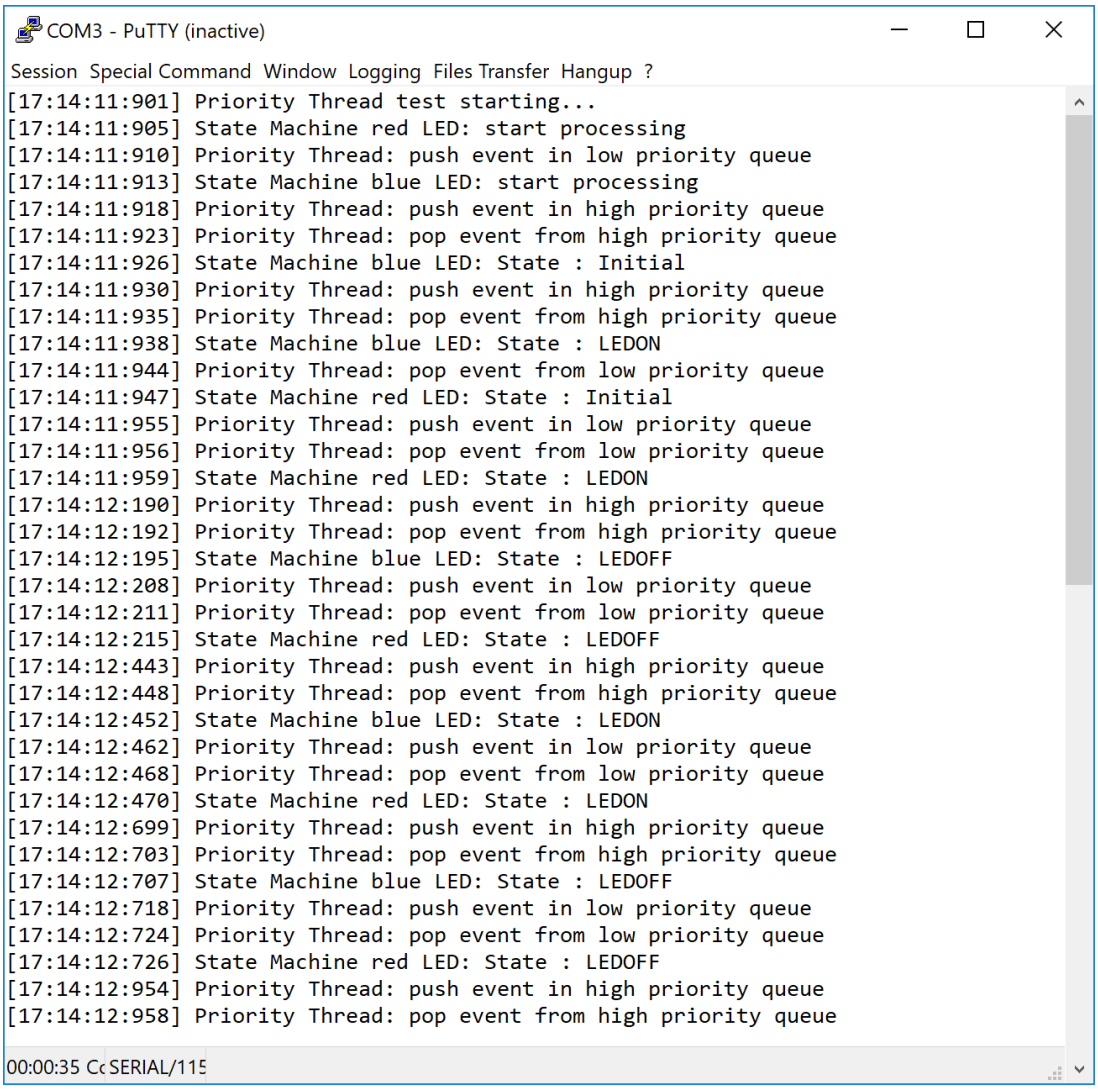


Figure 62 : Result of the priority thread test

At the beginning, it is the state machine red led that starts to process but the first Initial event processed is the one of the state machine blue led because it has a higher priority than the Initial event of the red state machine.

It proves that the priority thread works correctly.

12. Error handler test

This test checks if the error handler works correctly. In this test, the error handler is set and a thread is created with a bad value of priority. If the test works, the ErrorHandler must normally send on the serial port, a message that indicates that a priority error occurs during the creation of the thread.

Result

The Figure 63 shows the result of the Test.

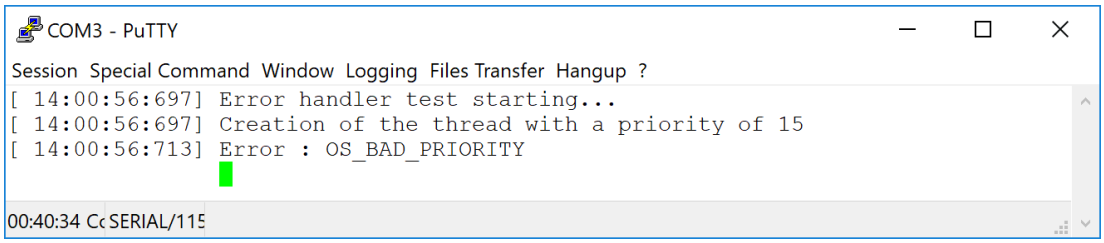


Figure 63 : Result of the error handler test

As expected, the error OS_BAD_PRIORITY occurs and the error handler displays that in the serial port.

13. Mutex, semaphore test

This test just checks if a mutex works correctly (as mutex and semaphore are same Free RTOS primitives, it is considerate that if mutexes work semaphores also work).

In this test, the UART is not protected from the concurrent access. Normally, if two threads try to write something in the same time, some messages will not appear.

Test code used to test it is the same as the multi state machine on multi thread test.

Result

The Figure 64 presents the output of the serial port if the UART is not protected with a mutex.

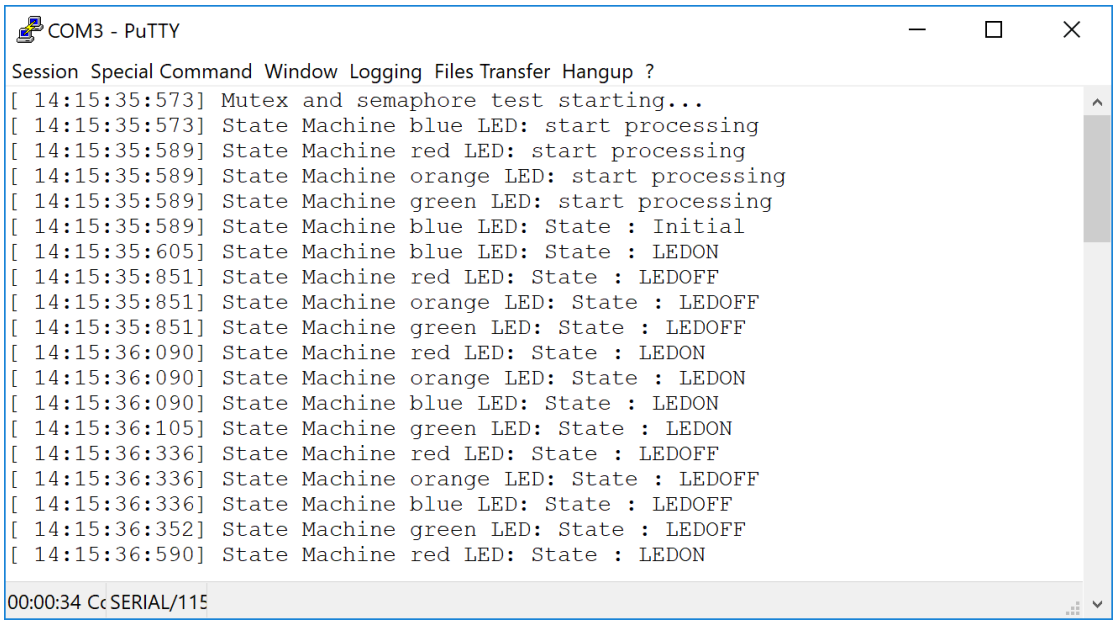


Figure 64 : Output of serial port without mutex

The initial state of blue led is displayed but the others Initial state not. The red led state machine directly goes in the LEDOFF but this is not a bad work of the system, just a concurrent access of several threads.

In the Figure 65, the mutex protect the UART.

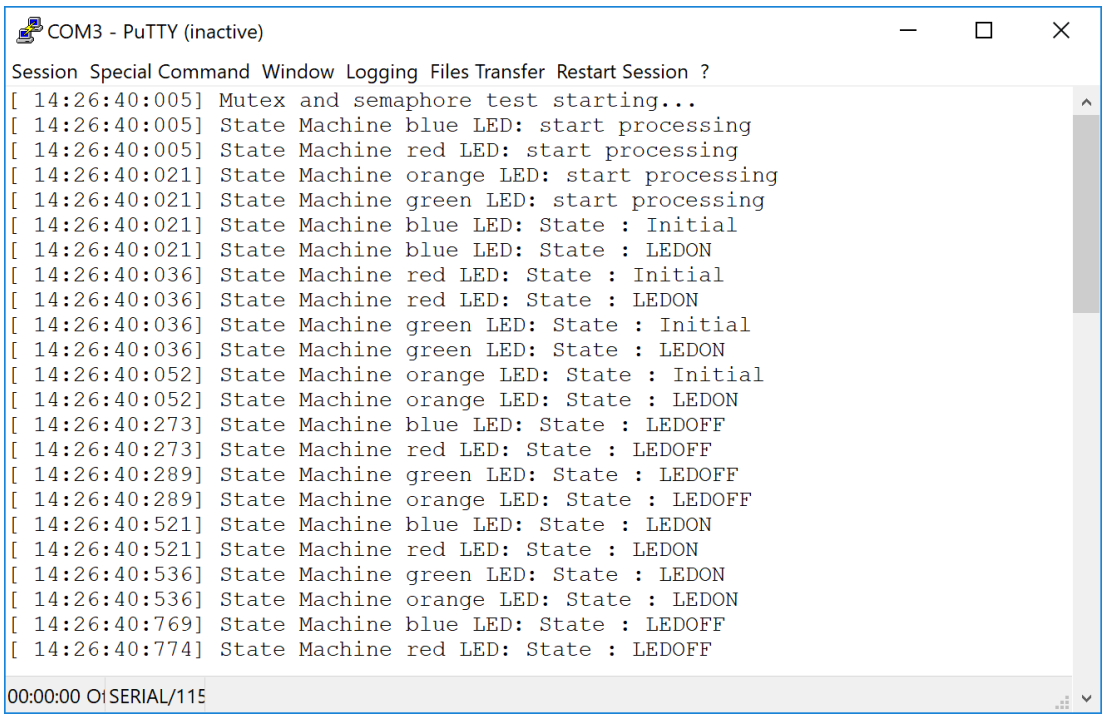


Figure 65 : Result of test with mutex

Here all states are correctly displayed in the serial port.

14. Timing precision

During the test of the delay event it was possible to see that the timing is not always respected. This error is due to the Free RTOS configuration, the define configTICK_RATE_HZ. This value is used as a source time by Free RTOS to generate a tick interrupt. The tick interrupt is used to unblock tasks and manage timers.

To know the real impact of configTICK_RATE_HZ on the precision of timers a set of measures has been made with different values of configTICK_RATE_HZ and different values of period times.

These tests are composed of 20 measures for configTICK_RATE_HZ of 50, 100, 250, 500 and 1000 and values of period of 50ms, 100ms, 250ms, 500ms and 1000ms.

configTICK_RATE_HZ 50

The Figure 66 presents the result of the measures for a configTICK_RATE_HZ of 50.

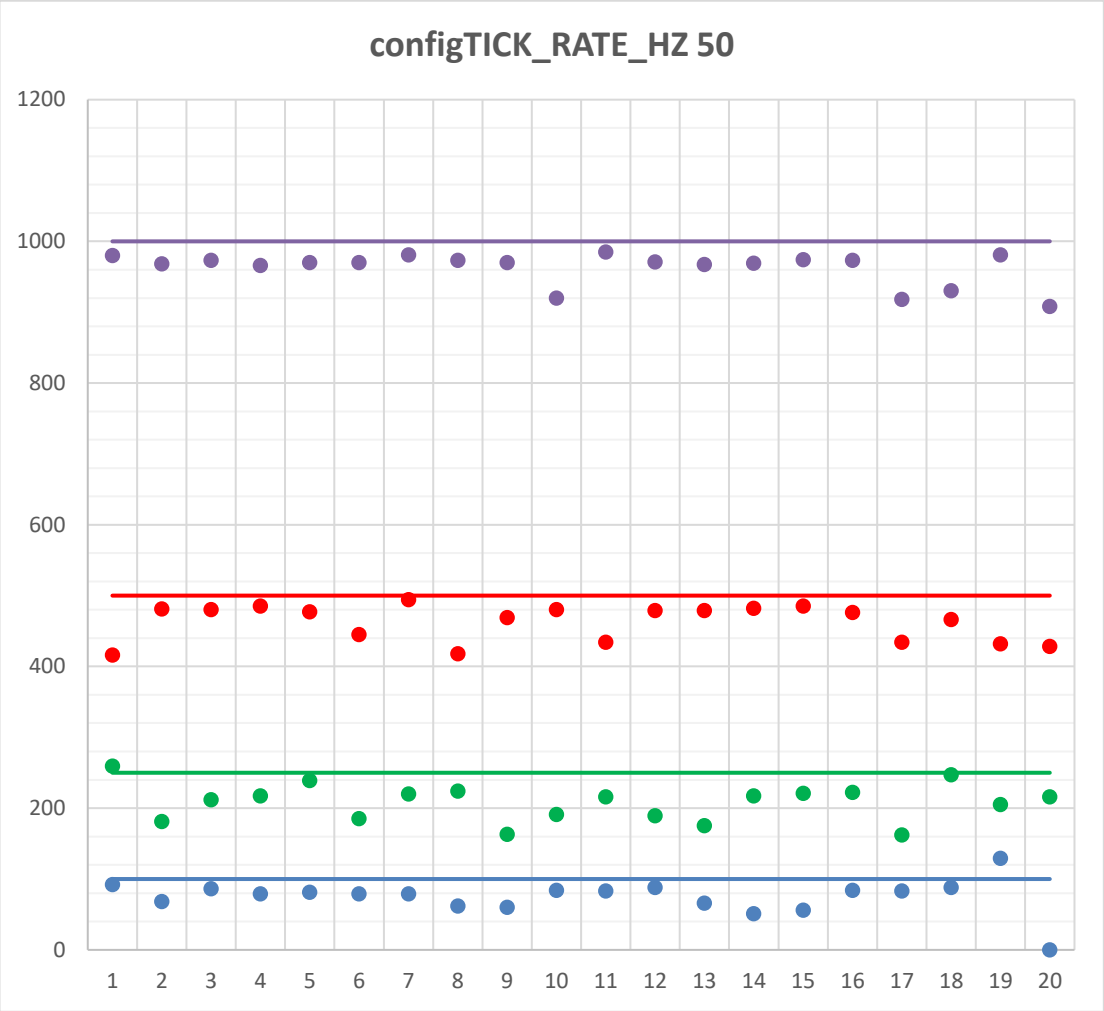


Figure 66 : Measure for a configTICK_RATE_HZ of 50

In blue are measures for a delay time of 100 ms. In green, a delay time of 250 ms. In red, a delay time of 500 ms and in purple, the delay time is 1000ms.

The measure points are the little dots and the line is the expected value.

This Figure shows that a great number of points are not accurate, especially for the delay time of 250 ms. It means that use a configTICK_RATE_HZ is very bad for timing precision.

It is interesting to note that most of errors are negative.

configTICK_RATE_HZ 100

The Figure 67 presents measures for a configTICK_RATE_HZ of 100.

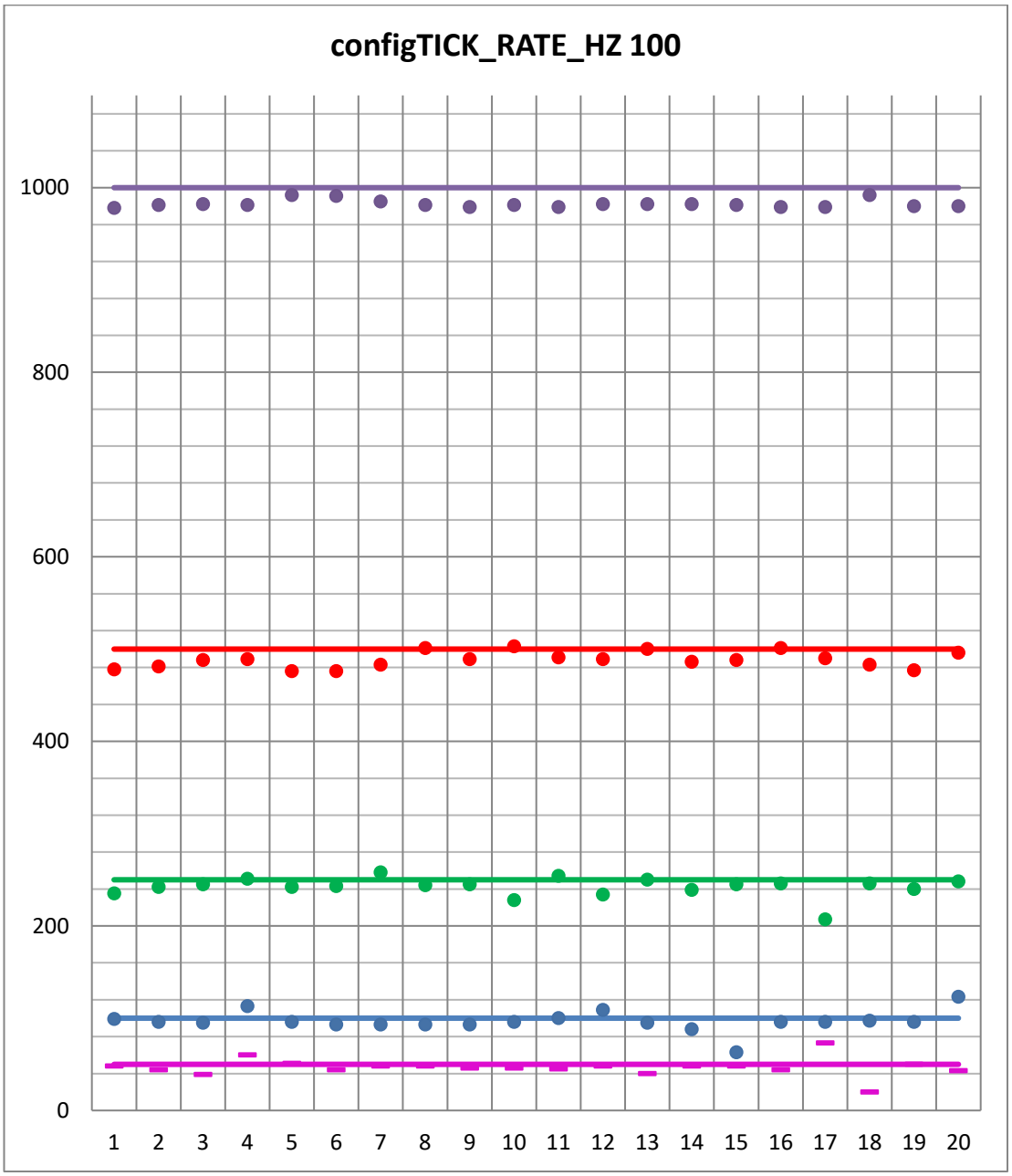


Figure 67 : Measure for a configTICK_RATE_HZ of 100

In pink are measures for a delay time of 50 ms. In blue are measures for a delay time of 100 ms. In green, a delay time of 250 ms. In red, a delay time of 500 ms and in purple, the delay time is 1000ms.

The measure points are the little dots (and dash for the 50 ms delay time) and the line is the expected value.

This graph shows that the delay time is better respected with a configTICK_RATE_HZ of 100, but measures for a delay time of 1000 ms are still approximate.

For a delay time of 50 ms, 100 ms and 250 ms, measures are relatively correct except one or two values which differ.

configTICK_RATE_HZ 250

The Figure 68 presents measures for a configTICK_RATE_HZ of 250.

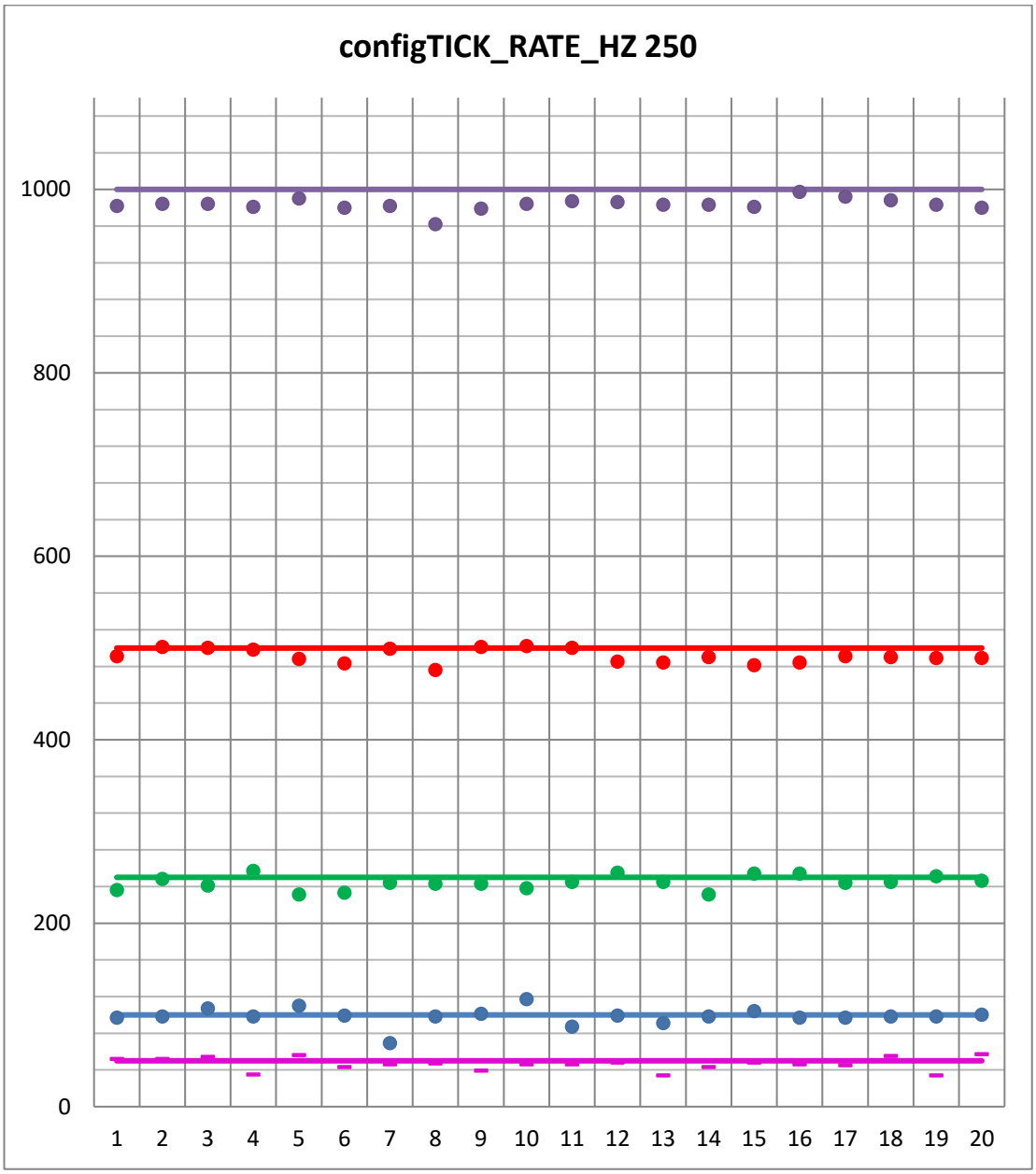


Figure 68 : Measure for a configTICK_RATE_HZ of 250

In pink are measures for a delay time of 50 ms. In blue are measures for a delay time of 100 ms. In green, a delay time of 250 ms. In red, a delay time of 500 ms and in purple, the delay time is 1000ms.

The measure points are the little dots (and dash for the 50 ms delay time) and the line is the expected value.

Here the observation is the same as for a config TICK_RATE_HZ of 100. For a low value of delay time, the timing is relatively respected. But for the delay time of 1000 ms measures are still approximate.

configTICK_RATE_HZ 500

The Figure 69 presents measures for a configTICK_RATE_HZ of 500.

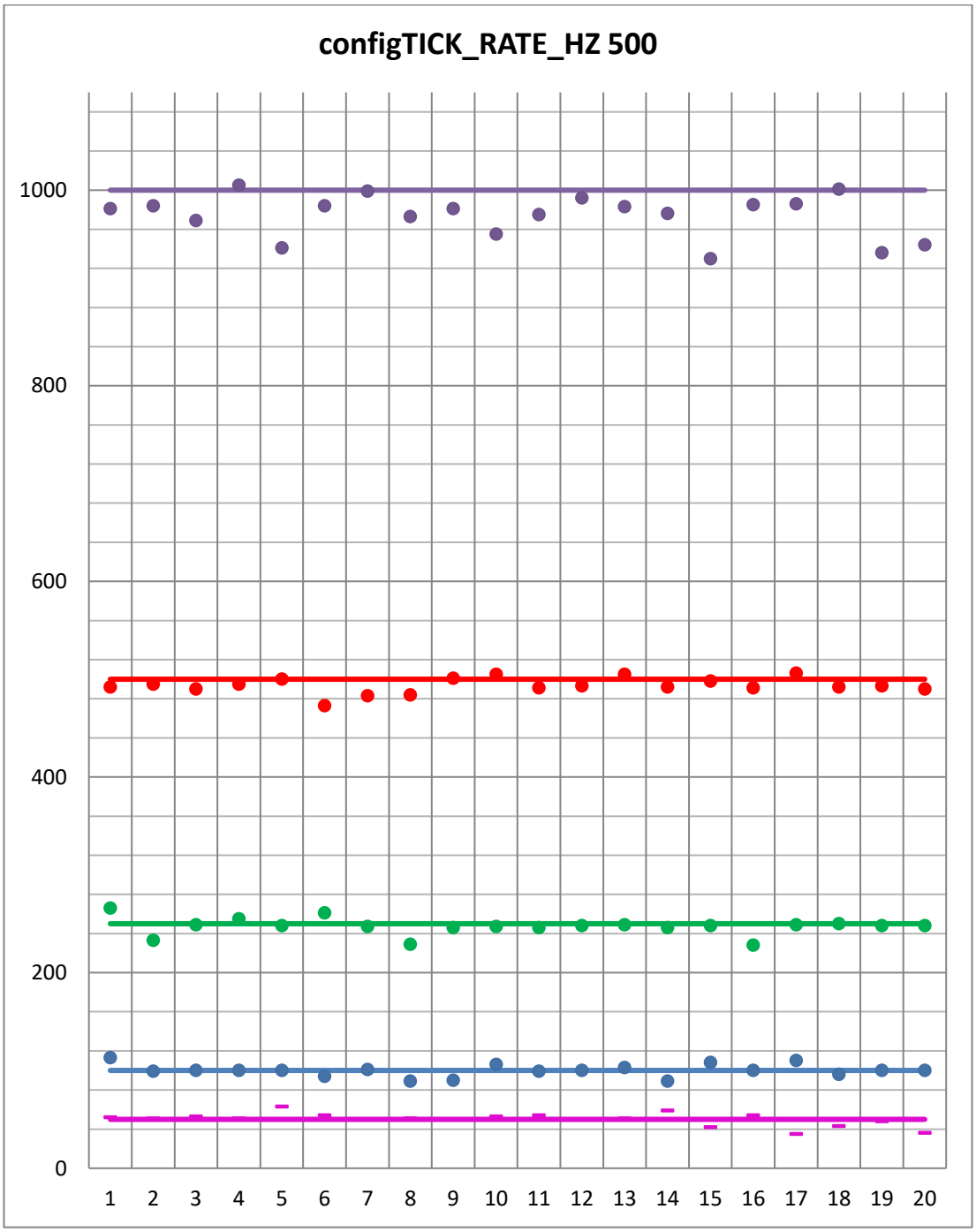


Figure 69 : Measure for a configTICK_RATE_HZ of 500

In pink are measures for a delay time of 50 ms. In blue are measures for a delay time of 100 ms. In green, a delay time of 250 ms. In red, a delay time of 500 ms and in purple, the delay time is 1000ms.

The measure points are the little dots (and dash for the 50 ms delay time) and the line is the expected value.

This Figure shows that low values of delay time are relatively correct but the values for 1000 ms of delay time are just catastrophic, the largest error is 70 ms.

configTICK_RATE_HZ 1000

The Figure 70 presents measures for a configTICK_RATE_HZ of 1000.

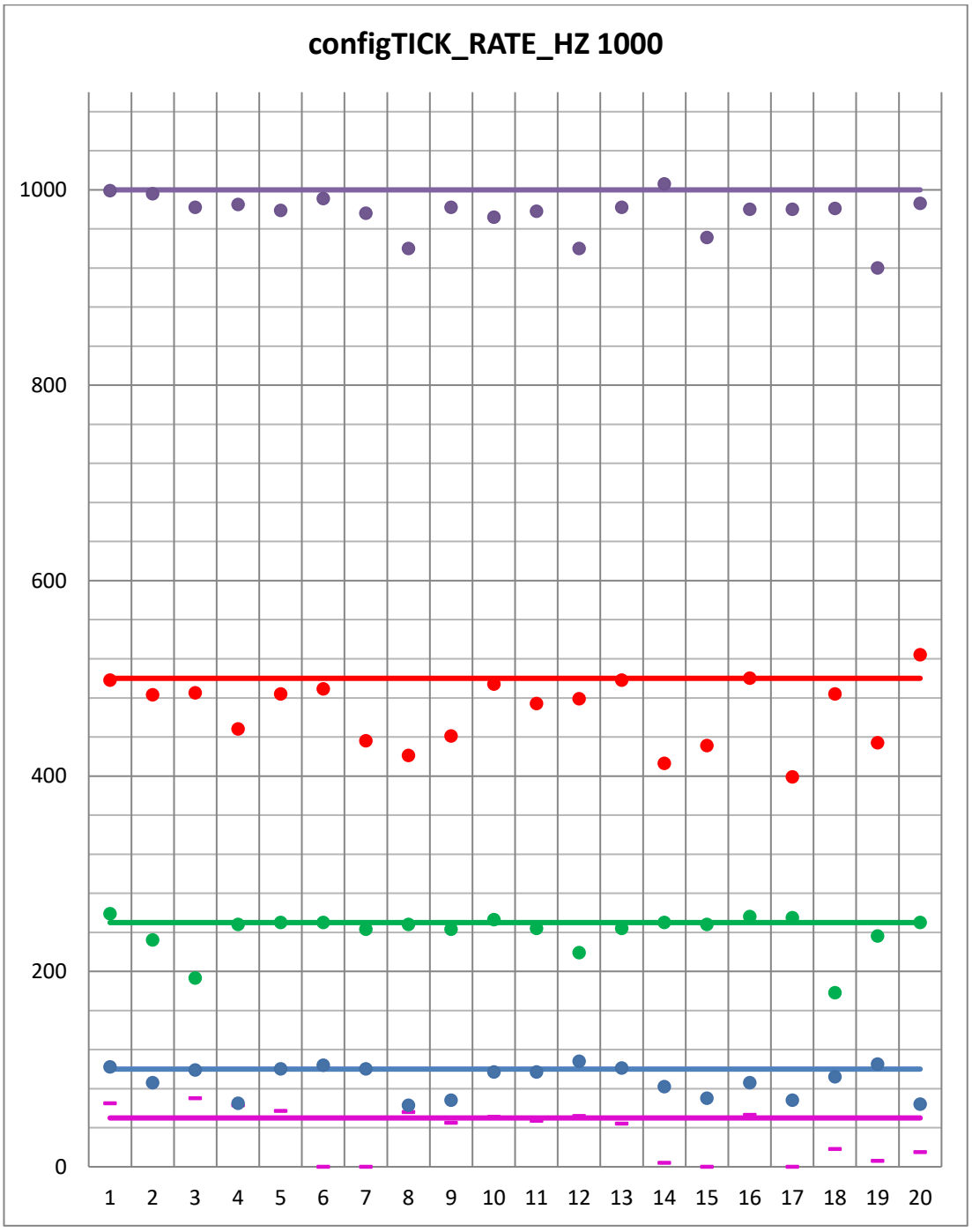


Figure 70 : Measure for a configTICK_RATE_HZ of 1000

In pink are measure for a delay time of 50 ms. In blue are measure for a delay time of 100 ms. In green, a delay time of 250 ms. In red, a delay time of 500 ms and in purple, the delay time is 1000ms.

The measure points are the little dots (and dash for the 50 ms delay time) and the line is the expected value.

Here it is the worst. So much measures are wrong and the absolute error is really large regardless of the delay time.

Conclusion

The first observation is that the highest mistakes are negative, it means that timers end generally before their period ends.

The highest mistakes happen when configTICK_RATE_HZ has the value of 50 and 1000.

For a medium value of configTICK_RATE_HZ (100, 250, 500) timing is mostly respected. But some big mistakes may appear.

In view of the random precision of the timers, it would be preferable not to use the XFOS in a system requiring high precision of timing.

IX. Google test code analyse

Google test is a unit testing library for C++ applications, based on a xUnit architecture. The library is released under the BSD 3-clause license [8].
Google test is platform-neutral, it works on different operating systems and with different compilers such as gcc, MSVC, and others.

1. Utility of google test

The Google testing framework offers a large set of features to simplify tests and debug.

1. Independent and repeatable: Google test isolates all tests and runs them independently and if a test fails, gtest allows the possibility to run it in isolation.
2. Well organized: In gtest, it is possible to group tests into test cases that can share data and subroutines.
3. Platform-neutral: Google C++ Testing Framework works on different OSes, with different compilers (gcc, MSVC, and others), with or without exceptions, so Google C++ Testing Framework tests can easily work with a variety of configurations.
4. Information about fails: when tests fail, they should provide as much informations about the problem as possible. Google C++ Testing Framework does not stop at the first test failure. Instead, it only stops the current test and continues with the next. You can also set up tests that report non-fatal failures after which the current test continues. Thus, you can detect and fix multiple bugs in a single run-edit-compile cycle.

[9]

2. Problems encountered

The principal problem with google test is that it does not work on a bare metal system (a system without OS), because it uses some OS primitives that uses the file system. But a bare metal system does not have any file system and do not implement these functions.

Solving problems

mkdir

The first undefined function is “mkdir” in the line 8109 of the gtest-all.cc file. This function is a Unix command that is used to make a new directory [10]. The Figure 71 shows the part of code that calls this function. The part in yellow is the one that fails in build.

```
bool FilePath::CreateFolder() const {
#if GTEST_OS_WINDOWS_MOBILE
  FilePath removed_sep(this->RemoveTrailingPathSeparator());
  LPCWSTR unicode = String::AnsiToUtf16(removed_sep.c_str());
  int result = CreateDirectory(unicode, NULL) ? 0 : -1;
  delete [] unicode;
#elif GTEST_OS_WINDOWS
  int result = _mkdir(pathname_.c_str());
#else
  int result = mkdir(pathname_.c_str(), 0777);
#endif  // GTEST_OS_WINDOWS_MOBILE

  if (result == -1) {
    return this->DirectoryExists();  // An error is OK if the directory
exists.
  }
  return true;  // No error.
```

Figure 71 : Google test code that call mkdir()

This function is used in gtest to create a new directory.

The build fails here because mkdir is not defined for the STM32 it only exists for an OS.

The solution proposed is to replace the function mkdir by 0.

```
  int result = 0;//mkdir(pathname_.c_str(), 0777);
```

Figure 72 : Solution for mkdir problem

This solution is acceptable because, after a test on a Windows environment, it seems that this part of code is never used in a simple test.

getcwd

Getcwd is the second undefined function is also a function that needs a file system. It gets the name of the current working directory, it is called at line 7891 of the gtest-all.cc file. The Figure 73 shows the part of code that call this function. The part in yellow is the failing part.

```
// Returns the current working directory, or "" if unsuccessful.
FilePath FilePath::GetCurrentDir() {
#if GTEST_OS_WINDOWS_MOBILE
  // Windows CE doesn't have a current directory, so we just return
  // something reasonable.
  return FilePath(kCurrentDirectoryString);
#elif GTEST_OS_WINDOWS
  char cwd[GTEST_PATH_MAX_ + 1] = { '\0' };
  return FilePath(_getcwd(cwd, sizeof(cwd)) == NULL ? "" : cwd);
#else
  char cwd[GTEST_PATH_MAX_ + 1] = { '\0' };
  return FilePath(getcwd(cwd, sizeof(cwd)) == NULL ? "" : cwd);
#endif  // GTEST_OS_WINDOWS_MOBILE
```

Figure 73 : Google test code that call getcwd()

This part is more complicate to modify because return "" means that the command fails and it is not possible to return a fake value because the current working directory does not exist in the system.

The solution choses is to replace the getcwd function by "" and see what happens during the execution of the program.

```
return FilePath("");//getcwd(cwd, sizeof(cwd)) == NULL ? "" : cwd);
```

Figure 74 : Solution for getcwd problem

Execution

After the two modifications presented above the gtest code built successfully but just after the function “getCurrentDir()” fails the program finish in a _exit and kills the process. It means that google test absolutely needs this current directory to work.

It is interesting to note that the function GetCurrentDir() is called before the begin of the main function. It means that it is called by a global object that is created before the main.

After some researchs, it is proven that the macro “TEST” used by google test to create test case, create a global object that needs this current directory to work correctly.

3. Conclusion about gtest

To work correctly, gtest uses OS primitives, so it could not directly work on a bare metal system.

When a test is created it generates a global object that needs access to the file system. If any test is created, any global object is created and the program starts the main function but the macro RUN_ALL_TESTS() finish in a hardfault.

The macro TEST creates a global object that saves some information about itself before the execution of the main and this is why it needs the file system.
The tests are executed by the macro RUN_ALL_TESTS() but they needs the information previously stored.

Solution proposed

In the future, to make google test works on embedded systems without OS, it is necessary to study exactly what are the information stored and try to find if it is possible to store them in the RAM rather than store them in a file.

Because of lack of time this could not have been made in the project.

X. Future adaptations

1. Adaptation for others operating systems

Others OSAL

This project aims to implement an XF that uses Free RTOS primitives. In a second step, it could be interesting to modify the OSAL part to adapt it to another OS or RTOS.

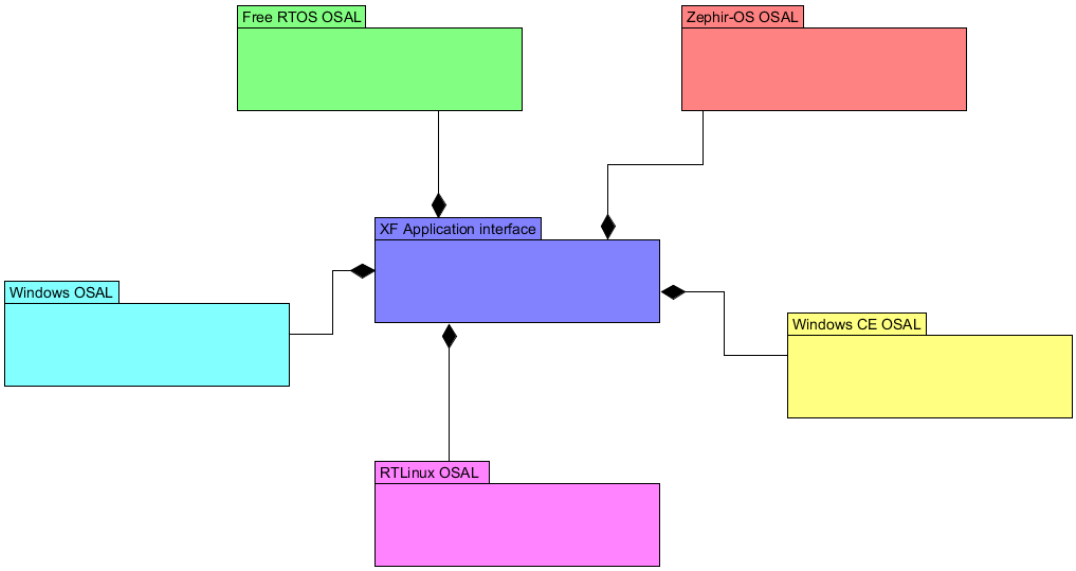


Figure 75 : Others OSAL

IDF

Sometimes, the use of an OS is unnecessary because it needs to much resources for the application uses. In this case, it could be useful to implement an XF but without OS. So, it could be really interesting if an IDF version of this project existed.

But an IDF is different from the simple OSAL developed on this project because it cannot implement all of its functionalities. If the XF application interface must not change, only the classes from the OSAL package can change, it means that classes of the OSAL package must emulate some functionalities of the OS.

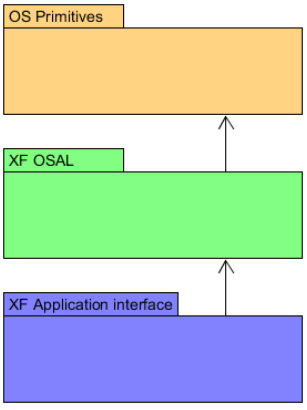


Figure 76 : The Actual XFOS packaging

In the Figure 76, the XF Application interface uses XF OSAL classes, it does not know the OS Primitives.

In the IDF the package OS primitives does not exists and the classes of the XF OSAL must simulate the OS Primitives work. As shown it the Figure 77.

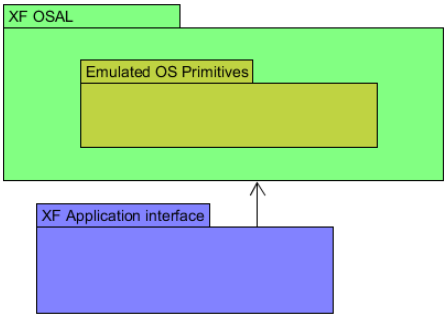


Figure 77 : IDF Packaging

Emulate the work of an OS is not easy, in the rest of this section, some solutions are proposed.

Semaphores and Mutexes

At first glance, semaphores and mutexes are useless in a mono thread environment like the IDF. But same if only one thread runs, a hardware interrupt could occur. In this case, it is interesting to implement critical sections that disables interrupts. This is not the same work as a semaphore or a mutex but it is important to not forget it.

ITimer

The class ITimer is just a simple abstraction of the OS Timers, without OS this class is useless. In the ECSG XF, software timers were just classes those had two values:

- timeoutTicks: the time to wait in tick (ticks are hardware timer period)
- remainingTicks: the number of tick to wait before the timer timeout

It is the work of the timeout manager to manage them. The timeout manager decreases the remaining ticks and determines if a timer ends.

In the XFOS, the timer manager just receives requests from threads, creates timers and informs threads when a timer ends.

The solution proposed is to implement the ECSG XF timeout manager in the ITimer class as a set of static members. The Figure 78 presents a possible class diagram for the IDF ITimer.

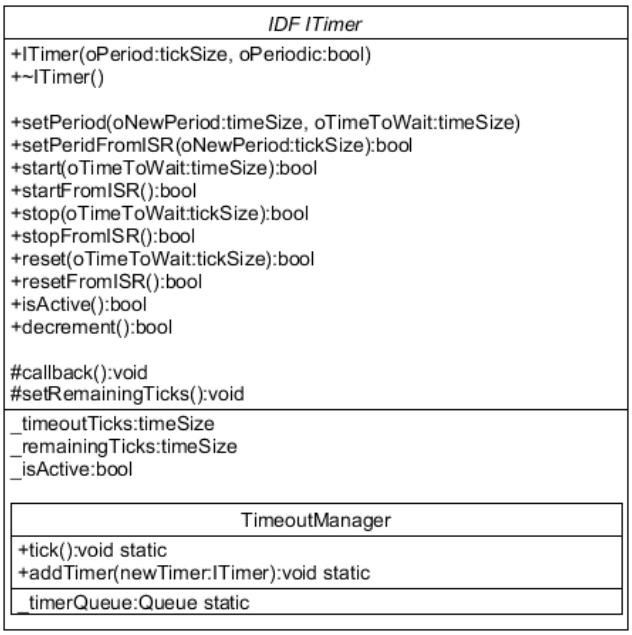


Figure 78 : Class diagram of IDF ITimer

In the constructor of the ITimer, the static method addTimer() is called. This method adds a pointer to the created ITimer in the _timerQueue, it is the same method as the one of the ECSG timeout manager.

The method tick() is called in a hardware timer interrupt. It calls decrement() that decrement _remainingTicks and check if this one is equal to null, if yes this call the method callback().

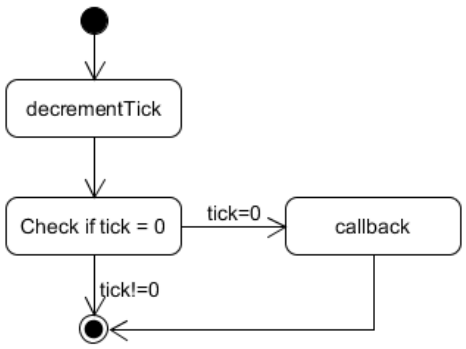


Figure 79 : State chart of decrement()

2. Priority thread

A PriorityThread is a Thread that dispatches first the high priority events. To do that, a priority thread must have the same number of event queues as of priority levels. For example, if a priority thread has two levels of priority, it must have two queues, one for the high priority and one for the low priority. During the push of the event, the priority thread checks the priority level of the event and pushs it in the good queue.

During the pop of the event, the priority thread must check if the highest priority queue contains events, if not it checks the lower priority queue, etc. for all queues. The Figure 80 shows this for two levels of priority.

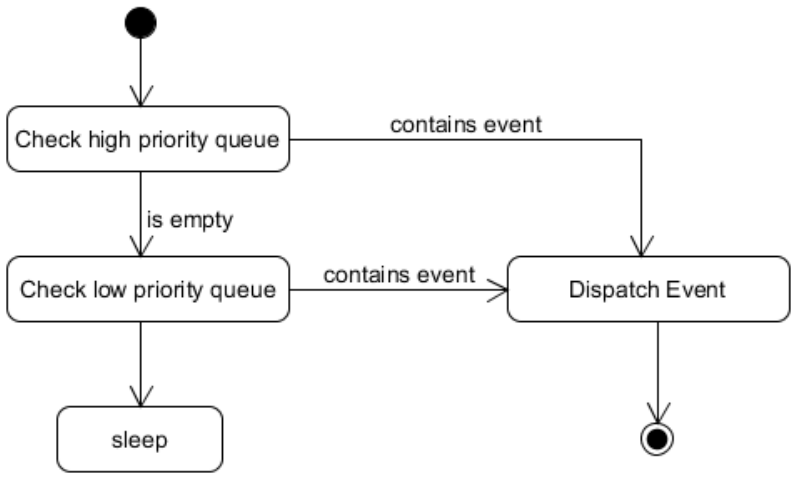


Figure 80 : Priority thread pop event for two levels of priority

A problem happens when the thread must sleep and wake up. A normal thread wakes up when an event is pushed in its queue and it falls asleep when the queue is empty. A priority thread falls asleep only when all of its queue are empty and must wake up when an event is pushed in any one of its queue. The problem is that is not possible to wake up a thread depending of many queues.

Solution

The solution proposed is to add one more queue than the number of priority levels. This queue just will wake up and asleep the thread.

When an event is pushed by a state machine, the priority thread will add this in the good priority queue and it will also add another useless event in the manage queue that will wake it up.

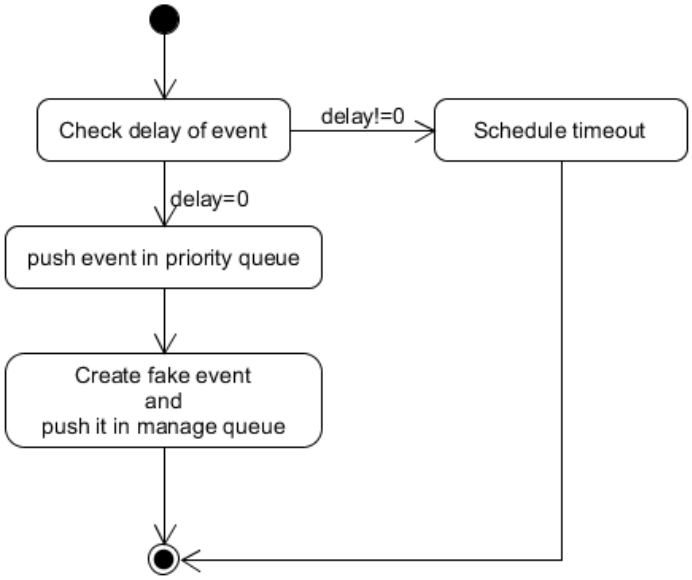


Figure 81 : Push event in a priority thread

During the pop, the priority thread will firstly check in the manage queue if an event has been pushed, if yes, it will check all priority queue and dispatch the event with the highest priority.

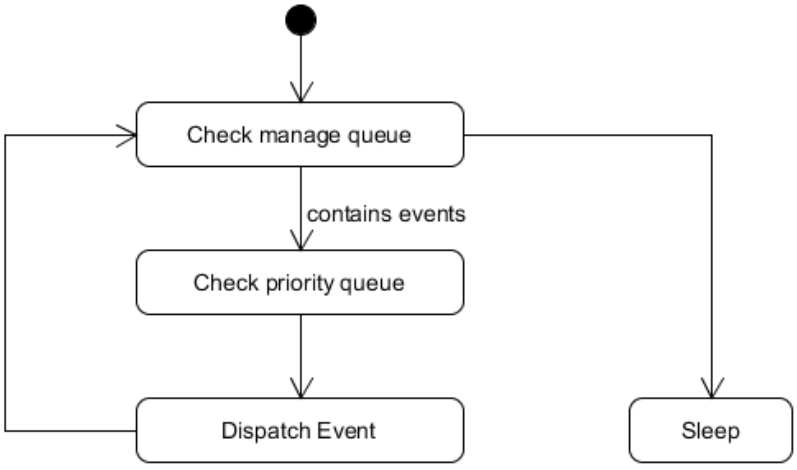


Figure 82 : Priority thread pop event

A version of a priority thread with two levels of priority has been developed for tests but this version is not optimal because it need a new implementation for all new priority level. In a future step, it could be interesting to develop a priority thread that get the number of needed priority levels.

XI. Conclusion

The development of the XFOS has been realized using Free RTOS for the board STM32F412G. The project is separated in two parts. An OSAL package, that depends of the OS used and implements all OS primitives needed for the proper operation of the XF. And an API package that does not depend of the OS used.

The XFOS implements all functions of the ECSG XF and offers new features such as multi-threading and an error handling system similar to exception handler supported by the C++, but better suited to the embedded system.

Tests demonstrate that a the XFOS supports all function of the ECSG XF and the communication between state machines, even if they are in different threads. It also offers the possibility to implement thread who manages the priority of the events.

Unfortunately, google test could not be used to realize the tests because it needs a file system to work correctly. To use gtest in a bare metal system such as the XFOS it is necessary to add a file system to the XFOS or modify the gtest code to ensure that the file system is not required.

A complete set of tests has been realized to check the proper work of the system. It tests the processing of events, the multi-threading and the communication inter-state machines The timing tests shows that the precision of timers is not optimal. Same with the best configuration the worst error is 13%.

A complete documentation, that defines and explains all classes of the project has been developed in the WIKI of the HES-SO, in the section “UIT” in the page “Components”.

Next steps

The next steps of this project could be the implementation of an OSAL part for others OS than Free RTOS and implement a version of the XFOS that works without OS.

To simplify the development of applications using the XFOS, it could be interesting to develop a graphic interface allowing the development of state diagrams and that converts graphs to C++ code.

XII. Bibliography

[1] M. Rieder, Execution Framework, 2016.

[2] M. Rieder, Execution Framwork (XF) Optimized Timer Management, 2016.

[3] Free RTOS, "RTOS-software-timer.html," [Online]. Available: http://www.freertos.org/RTOS-software-timer.html. [Accessed 15 Mai 2017].

[4] FreeRTOS, "RTOS-software-timer-service-daemon-task.html," [Online]. Available: http://www.freertos.org/RTOS-software-timer-service-daemon-task.html. [Accessed 15 Mai 2017].

[5] FreeRTOS, "xSemaphoreCreateBinary.html,," [Online]. Available: http://www.freertos.org/xSemaphoreCreateBinary.html. [Accessed 15 Mai 2017].

[6] R. Damon, “freertos_Is_it_possible_create_freertos_task_in_c_3778071.html,” July 2010. [Online]. Available: http://www.freertos.org/FreeRTOS_Support_Forum_Archive/July_2010/freertos_Is_it_possible_create_freertos_task_in_c_3778071.html. [Accessed 13 Jun 2017].

[7] M. Rieder, DeSem Embedded Software Engineering Patterns, 2017.

[8] Wikipedia, “Google_Test,” [Online]. Available: https://en.wikipedia.org/wiki/Google_Test. [Accessed 24 July 2017].

[9] “googletest/docs/Primer.md,” [Online]. Available: https://github.com/google/googletest/blob/master/googletest/docs/Primer.md. [Accessed 24 July 2017].

[10] Wikipedia, “Mkdir,” [Online]. Available: https://en.wikipedia.org/wiki/Mkdir. [Accessed 24 July 2017].

XIII. Annexes

1. Create a project to use XFOS, Free RTOS and the board STM32F412
2. Create a project using Google test C++ framework
3. Timing measurements
4. Specification of the Bachelor's Thesis
5. Resume

Date
25.08.2017

Signature